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Robert J Vidmar and Kenneth R Stalder

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University of Nevada, Reno
Sponsored Projects, Mail Stop 325
1664 N Virginia Street
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COMPUTATIONS OF THE POWER TO SUSTAIN PLASMA IN AIR WITH RELEVANCE TO AEROSPACE TECHNOLOGY

By: ROBERT J VIDMAR AND KENNETH R STALDER

Prepared for:

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
4015 WILSON BOULEVARD, ROOM 713
ARLINGTON, VA 22203-1954

CONTRACT NUMBER: F49620-01-1-0414

University of Nevada, Reno
1664 North Virginia Street
Reno, Nevada 89557-0240 USA

ABSTRACT

Research on the air chemistry for plasma produced by an electron beam and sustained with an electric field quantified the power to generate plasma with a density of 10^{10} cm^{-3} to 10^{13} cm^{-3} from sea level to 300,000 ft. An air chemistry code was upgraded and optimized for air-plasma research with key reactions that are functions of the reduced electric field, E/N, with a maximum value of 2×10^{-15} V-cm^2. A tabulation of all the reactions used and their reaction rates or graphical references document the air-code chemistry. The air code computes the concentration of electrons, all air species including water vapor and many byproducts such as O, many negative and positive ion species, oxygen singlet delta, oxygen vibrational states, energy deposited in the plasma, thermal expansion, the bulk gas temperature, and total power. Simulations suggest that a global minimum in power occurs as a function of E/N and roughly corresponds to a minimum in electron attachment to oxygen. Power reduction depends on the electron concentration, altitude, and duration of electron bombardment. Results suggest conditions where electron-beam bombardment converts air plasma into one where the excited-state concentrations are significant and influence the overall gas kinetics.

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I INTRODUCTION

The overall goal is to provide research on the generation and sustainment of atmospheric plasma with relevance to aerospace and biological applications. This plasma would have an electron density typically in the range of 10^{10} to 10^{13} electrons/cm^3 and operate in ambient air from sea level to 300,000 ft. The DoD has many applications for plasma in air ranging from bio-decontamination, coating of implants, plasma surgery, plasma assisted combustion in aircraft engines, hydrodynamic flow control on aerodynamic surfaces, supersonic shock-wave mitigation, plasma mirrors, rf effects; and high intensity rf propagation through a transmission window into air. For many of the aerospace and biological applications a practical efficient source is important. The particular ionization system is often chosen in conjunction with a consideration for practical issues, such as fast airflow, portability, set-up time, and uses that do not readily accommodate external electrodes. Consequently, direct electrical discharges were not considered. Impact ionization by a fast electron beam was considered because it requires no electrodes, can propagate a substantial distance into air, and is very efficient. The air-chemistry code and subsequent computations of power are all based upon plasma generation via an electron-beam source.

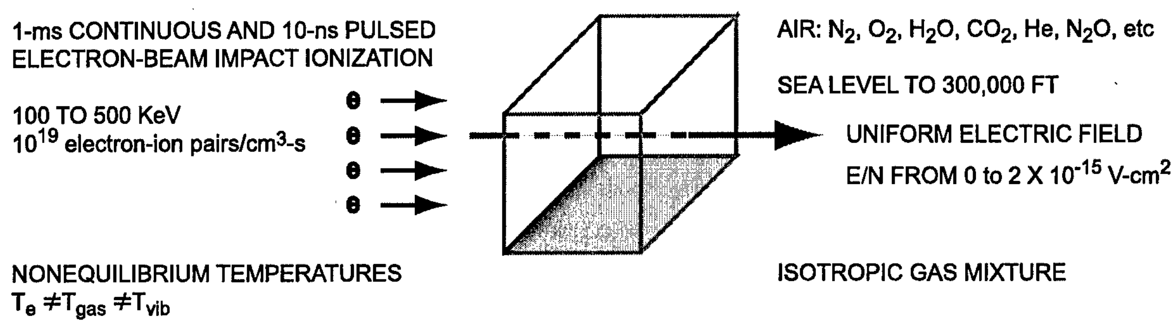
An early set of 1/e plasma lifetimes calculated by Vidmar (1990) suggested that substantial power was required to generate and sustain plasma in air where all species were in thermal equilibrium. Subsequent research by Yu *et al* (2002) for air heated to 2,000 K, Stark and Schoenbach (2001) for dry air at 2,000 K, Macheret *et al* (2001) for ambient air to 700 K, and Adamovich (2001) for optically pumped $CO/Ar/O_2$ and $CO/Ar/N_2$ mixtures at 700 K has shown that a nonequilibrium plasma requires less power than an equilibrium plasma. The theoretical research conducted explored transient nonequilibrium electron-beam generated plasma, where the typical time scale was approximately 1 ms and the bulk gas temperature was kept near ambient.

II TECHNICAL APPROACH

A. Computational Modeling

Earlier research on electron-beam generated plasma, Vidmar (1990A), resulted in an air chemistry code that has subsequently been refined. The code as noted in Fig. 1 is zero dimensional and assumes an isotropic gas mixture. Air with water vapor is the target gas and represents a standard atmosphere from sea level to 300,000 ft. Additional options allow the modeling of synthetic air and helium-air mixtures. Electron beam impact ionization is the primary ionization source, which generates a number of positive, negative, and excited state byproducts that are quantified in Vidmar and Stalder (2004). A uniform electric field can be modeled with values of reduced electric field, E/N, ranging from 0 to 2 x10^{-15} V-cm^2, where E is electric field strength and N is bulk gas number density The code permits nonequilibrium conditions among electrons, vibrational states, and the bulk gas temperatures.

CUBE: 1-cm ON EDGE



COMPUTATIONAL PARAMETERS: 58 SPECIES AND 461 REACTIONS

SPECIES: 14 NEUTRAL, 15 EXCITED STATES, 15 NEGATIVE, AND 14 POSITIVE

EXPERIMENTAL DATA USED FOR HIGH E/N, WHEN AVAILABLE

E/N DEPENDENCIES CODED AS TABLES

BULK GAS TEMPERATURE AND GAS EXPANSION

EXPLICIT JACOBIAN

COMPAQ FORTRAN: LAPTOP AND MINICOMPUTER

$$\frac{dy_i}{dt} = f_i(t, y_1, y_2, \ldots, y_{58}) + R_i\, g_i(t) \qquad i = 1, 58$$

$$f_i = y_i \sum_{j=1}^{58} n_{ij}\, k_{ij}(E/N)\, y_j + y_i \sum_{j=1}^{58} \sum_{m=1}^{58} n_{ijm}\, k_{ijm}(E/N)\, y_j\, y_m$$

Figure 1 Computational model overview.

The air chemistry code solves a set of coupled nonlinear equations with source terms as noted in Fig. 1. In Fig 1, the quantity y_i refers to the concentration of the i^{th} species, t is time, R_i is the magnitude of a source term, $g_i(t)$ is the time dependence of a source term; $k_{ij}(E/N)$ is a two-body reaction rate that may have an E/N dependence, $k_{ijm}(E/N)$ is a three-body reaction rate that may have an E/N dependence, n_{ij} is a signed integer constant that depends on detailed balance of each two-body reaction, and n_{ijm} is

a signed integer constant that depends on detailed balance of each three-body reaction. The species, properties of the species, reactions, reaction rates, and reaction-rate references are quantified in Appendix A. The air code tracks energy deposition by the electron beam and Joule heating when an electric field is present. Bulk gas heating is computed based on net energy deposition in the gas.

The linear equation solver runs with an explicit Jacobian, which increases accuracy and greatly reduces computational run time. The additional speed of the code facilitated an increase in species and reactions without a burdensome increase in run time. There remains sufficient headroom for additional species and reaction to be added in the future. The air code was programmed in Compaq Visual Fortran and runs most simulations in less than a minute.

The code has three primary modes of operation. The first mode is a delta function mode that was part of the original code in Vidmar 1990A and used to generate the 1/e plasma lifetime curves in Vidmar 1990B. The second mode is a constant level of ionization that was run for durations of as long as 1 ms and used to generate the species and power curves in Vidmar and Stalder (2003 and 2004). The third mode is a repeating rectangular pulse sequence to simulate the effects of repetitive pulsing. An example of a 100 ns on-off pulse sequence appears in Vidmar and Stalder (2004).

B. <u>Reduced Electric Field.</u>

One result of modeling attachment in oxygen and oxygen-nitrogen mixtures is a well-developed minimum for attachment as a function of E/N as explained by Taniguchi *et al* (1982). It was apparent that electron attachment to O_2, electron detachment from O^- and O_2^-, metastable production, and ionization should be quantified in the air code, as a function of E/N. An additional detail in modeling air as a function of E/N, however, is the effect of water vapor on the electron energy and momentum transfer collision rate. An appropriate formulation was found in Lowke (1992) and the results incorporated in the air code as a function of both percent H_2O and E/N

Aleksandrov (1993) provides a theoretical analysis of electron three-body attachment to O_2, $O_2(a^1\Delta_g)$, and their vibrational states as a function of E/N. Although the attachment rate to O_2 is high, attachment to $O_2(a^1\Delta_g)$ is several orders of magnitude lower. The attachment rate for vibrationally excited O_2 decreases for increasing vibrational levels. But, the attachment rate for vibrationally excited $O_2(a^1\Delta_g)$ increases for increasing vibrational levels but remains approximately two orders of magnitude lower than the attachment rate to ground state O_2. It is clear that kinetic processes that generate $O_2(a^1\Delta_g)$ and vibrationally excited O_2 lead to lower overall attachment rates. Consequently, reactions with E/N dependencies for electron excitation of $O_2(a^1\Delta_g)$, impact excitation of the first four vibrational levels of O_2, and electron detachment from O^- and O_2^- were added to the code. The electron temperature and these rates in graphical form appear in Vidmar and Stalder (2003 and 2004).

C. Druyvesteyn Distribution.

Electron Energy Distribution Functions The electron energy distribution function (EEDF) can dramatically influence the rate constants for electron impact processes. The Boltzmann equation is frequently used to deduce the EEDF when the appropriate cross sections for momentum transfer and inelastic energy loss are known. Intuition suggests that at low E/N a Maxwellian distribution function would result. However, Druyvesteyn found that low E/N conditions produce a distorted distribution function in which the high-energy population is reduced from the Maxwellian population. Nevertheless, many researchers report rate constants as a function of an electron temperature, regardless of the value of E/N applicable to their conditions. Sometimes rate constants are specified in terms of the reduced electric field, E/N, and in some of those reports an analysis of the Boltzmann equation is used to determine the EEDF and its departure from a Maxwellian. The analytic form of the EEDF originally attributable to Druyvesteyn may more closely approximate the actual form of the EEDF derived from solving the Boltzmann equation, see Smirnov (1981) or Behnke (1998). Lowke's (1992) Boltzmann analysis shows mean electron energies (D/μ) and drift velocities for dry air and humid (2%) air, but does not show the EEDF explicitly. The analysis of Aleksandrov *et al* (1981) resulted in tabulations of the EEDF for dry synthetic air for high values of E/N (>3 $\times 10^{-16}$ volt cm^2); these data indicate the EEDF has both Maxwellian and Druyvesteyn-like features. Because the EEDF is not evaluated in the air code, the precise form of the distribution function as the air chemistry evolves is not known.

Many reactions in the literature are expressed in terms of cross sections as a function of energy. Rate constants are derived from cross sections by averaging the cross section over velocity, where the average is computed using the appropriate distribution function. The following section summarizes analytic techniques for representing reaction rates in terms of the EEDF and cross sections.

Rate Constants and the EEDF. The rate of reaction (in numbers of particles per cubic centimeter per second) between two colliding particles (denoted by indices a and b) may be generally expressed at $R=k\,N_aN_b=\langle\sigma v\rangle_{ab}\,N_aN_b$, where N_a and N_b are the densities of each type and the rate constant $k=\langle\sigma v\rangle_{ab}$ is the velocity-averaged cross section that is determined by both the velocity dependence of the cross section as well as the form of the distribution function used to compute the average (denoted by the brackets <>). In the case of electron collision processes with much heavier atoms, molecules and the like, the electron velocities are usually substantially greater than the heavy particle's, so the average may be reduced to just averaging over the electron velocity distribution. It is conventional in many gas discharge studies to use the electron's energy distribution function (EEDF) rather than its velocity distribution. Then the rate constant k_i for reactions with electrons may be expressed in terms of the EEDF $f_o(U)$ as

$$k_i=\left(\frac{2e}{m_e}\right)^{1/2}\int_0^\infty Uf_o(U)\sigma(U)dU\ ,$$

where $\sigma(U)$ is the cross section for the process *i* as a function of energy *U*. For Maxwellian EEDFs,

$$f_o(U) = C\exp\left(\frac{-U}{k_B T_e}\right),$$

where *C* is a normalization constant and k_B is Boltzmann's constant. For Druyvesteyn distributions, the EEDF may be expressed as

$$f_o(U) = A\frac{1}{U_e^{3/2}}\exp\left[-\frac{1}{k}\left(\frac{U}{U_e}\right)^k\right], \text{ with } A = \frac{\left(\frac{1}{k}\right)^{\frac{(3-2k)}{2k}}}{\Gamma\left(\frac{3}{2k}\right)}.$$

where U_e is the effective temperature which is equal to the mean energy, Γ is the gamma function, $k \approx 2$ for Druyvesteyn distributions, and A = 0.9704 for $k = 2$..

Figure 2 contains several forms of the EEDF relevant to air that appear in the literature. It is clear that for many processes in which the cross section is sizable for energies above about 2 eV, large variations in the rate constant would be obtained depending on the form of the EEDF used. The code does not evaluate the EEDF at each time step because of the complexity and time consumption of calling a Boltzmann equation solver at each time step and the lack of sufficient cross section information for all of the processes and species modeled in the air-chemistry code. Approximate methods are used to carry out the air chemistry calculations. Many electron impact rate constants are expressed as a function of the electron temperature T_e, in which Maxwellian EEDFs are implicitly assumed. Some authors express rate constants as a function of the reduced electric field E/N, and some of these are actually computed from EEDFs that are computed from solving the Boltzmann equation for particular gases or gas mixtures. The rate constants used were derived from many sources and are expressed in terms that most closely reflect the particular situation being modeled. Experimentally derived rate constants for air, including water vapor are preferred, but occasionally theoretically-derived values are used when experimental data does not cover all of the conditions encountered during the simulation. In some cases rate constant data is interpolated or extrapolated to extend the ability of the code to deal with the widely varying conditions encountered in the simulations.

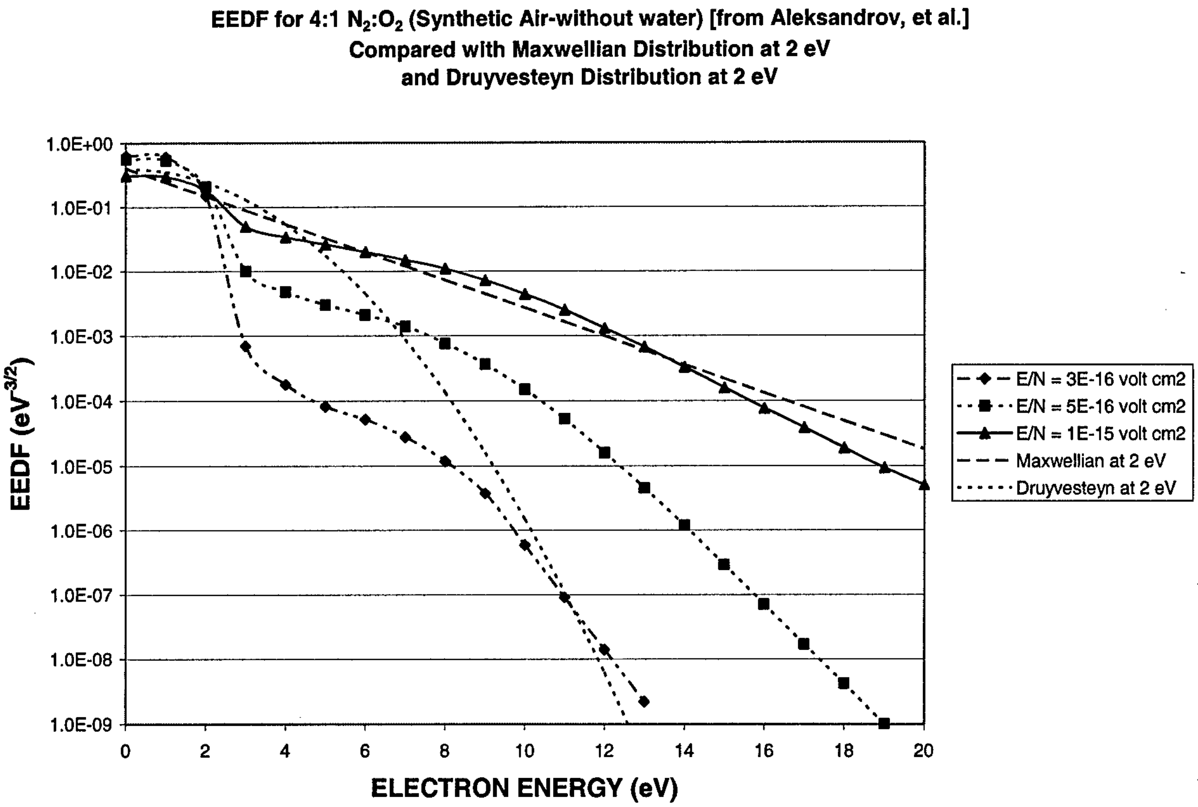


Figure 2 Comparison of Maxwellian and Druyvesteyn EEDFs at 2 eV.

D. Power.

The computation of net power deposited in the plasma is the sum of the electron beam power and Joule heating. For each time step in the simulation, the air code evaluates the net energy deposited in the plasma. The energy from the electron beam is based on a deposition of 33.7 eV for each electron ion pair plus the Joule heating based on the value of electric field and the DC conductivity. The net power calculated for a finite time interval is an average power or total energy deposited divided by the simulation time interval. All of the energy deposited in the plasma is tracked as a function of time. That energy is used to compute the bulk gas temperature.

E. Pulsed Electric Field Effects.

For many applications, pulsed sources are used. As noted above, there are many reactions that depend on E/N. Because one of the detractors to many applications is the necessity of external electrodes, a means of generating an external electric field without external wires is an important advance. Macheret et al (2001)

provides specific insight to the external axial electric field produced by an electron beam propagating in air. Their work quantifies the axial electric field and relates it to the beam current and energy. The same physical processes that produce the axial electric field will be present for a pulsed system. In a simplistic way, the beam current per pulse will control the value of E/N in the plasma when the beam is on. When the beam is off, the axial electric field decays to zero.

The effect on the species concentrations can be immense. The production of $O_2(a^1\Delta_g)$, for example, has a reaction rate of 1×10^{-13} cm^3/s and 2×10^{-11} cm^3/s for E/N = 10^{-17} V-cm^2 and 10^{-16} V-cm^2, respectively. Suppose a steady continuous beam produced an E/N of 10^{-17} V-cm^2 in the plasma, the average reaction rate for production of $O_2(a^1\Delta_g)$ would be 1×10^{-13} cm^3/s. For a pulsed system with a 10% duty ratio and the same average power, the current would increase by a factor of 10 and the value of E/N would be 10^{-16} V-cm^2 when the pulse is on. The average reaction rate would increase to 2×10^{-12} cm^3/s, an increase of 20. The pulse magnitude and duty ratio provide a means of regulating E/N and the underlying plasma air chemistry without the utilization of external electrodes.

The ability to adjust the value of E/N without external electrodes to produce a variety of air-chemistry effects provides a means of producing custom excited state mixtures for a variety of purposes. For example, air plasma rich in excited states would reduce the overall electron attachment rate and reduce power expenditure. For bio-decontamination a plasma rich in O and other radical species would be appropriate. The value of E/N to minimize power and maximize O and radical species production are different but both can be achieved using a pulsed system without external electrodes.

III RESULTS

The major research results are the following:

- Development of a substantial bibliography on air-plasma gas kinetics.
- Publication of graphs of important reaction rates as a function of E/N.
- Development of a gas-kinetics code optimized for air-plasma research.
- Quantifying the power per unit volume for air plasma from sea level to 300,000 ft.
- Quantifying excited-state concentrations for air plasma.

A. Air-Plasma Gas Kinetics Bibliography

The literature search for materials that bear on the gas kinetics of air plasma resulted in an extensive bibliography of over 500 references including references from many translated European and Russian journals. The bibliography has been included as an attachment to a book by Becker, K. H., R. J. Barker, and K. H. Schoenbach, *Non-Equilibrium Air Plasmas at Atmospheric Pressure,* to be published by Institute of Physics in 2004.

B. Reduced Electric Field

The key reaction rates with strong dependence on E/N and the dependence of electron temperature as a function of E/N and water vapor concentration were published in Vidmar and Stalder (2003). The practical range of E/N for these reactions is from 0 to 2 $\times 10^{-15}$ V-cm^2. The rates include electron three-body attachment to oxygen with O_2 and N_2 as the third body, electron dissociative attachment, electron detachment from O^-, collisional detachment from O_2^- with N_2 or O_2 as the second body, electron impact ionization of O_2, and impact excitation of $O_2(a^1\Delta_g)$.

Because the excitation of N_2 and O_2 vibrational states can have large reaction rates for large values of E/N, they were investigated and included in the air code. The electron excitation reaction rates of the first four vibrational levels of O_2 and N_2 were extracted from Aleksandrov *et al* (1981) and Pavlov (1998A and 1998B) and appear in Fig 3. For $E/N \leq 1 \times 10^{-17}$ V-cm^2 the production of oxygen vibrational states dominates over nitrogen vibrational states. For $E/N > 1 \times 10^{-17}$ V-cm^2 the production of nitrogen vibration states dominates by over an order of magnitude.

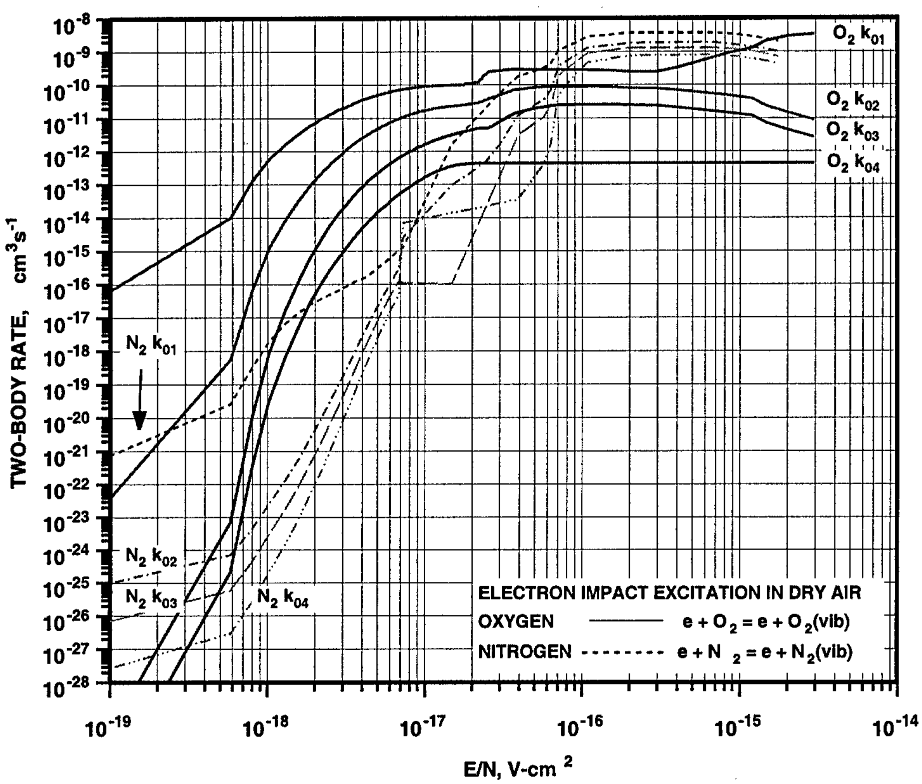


Figure 3 Electron impact excitation of vibrational levels in N_2 and O_2.

C. Air-Plasma Code

The initial air-chemistry code from the late 1980's has been transformed into a useful research tool. Key features are the ability to model air plasma from sea level to 300,000 ft, to model helium-air mixtures, impose a continuous electric field, model delta-function, continuous ionization, and repeating rectangular pulses; and to output files that track all species, energy deposition processes, gas expansion, and temperatures. The code implements all of the species and reactions noted in Appendix A and the nonlinear equation solver operates with an explicit Jacobian for the time derivative of the species concentrations. There is ample headroom to accommodate many additional species and reactions, such as collisional dissociation of N_2, O_2, O_3, and other species that would permit more accurate simulations with a gas temperature in excess of 1,000 K. These features permit a wide range of simulations that can be used to estimate total power required to generate and sustain plasma and can provide theoretical curves for comparison to electron-beam air-plasma experiments, such as Kiselev *et al* (1979), Andreev *et al* (1985), and Spencer *et al* (1987). All of these experiments report longer plasma lifetimes and lower power than would be expected based on electron three-body attachment to oxygen.

D. Power

Although some applications of plasma, such as a shock wave, plasma torch, or hot exhaust gases, operate at high temperature near 2,000 K, biological applications and low temperature applications on or near an aircraft require bulk gas temperatures at or near ambient. The approach of using an electron-beam to generate and sustain plasma does not require any preheating of air and therefore accommodates ambient and low temperature applications. A sampling of net power expenditure reports for a plasma density of $n_e = 10^{13}$. cm^{-3} plus their operating conditions and the current results of this effort appear in Table 1.

Table 1 Power per Unit Volume for an Air Plasma with $n_e = 10^{13}$. cm^{-3}

Source and Conditions	P/V	Reference
Electron-beam source with 2,000 K preheated air continuous operation	100 MW/m^3 (100 W/cm^3)	Macheret et al (2001)
Direct current glow discharge with 2,000 K preheated air and a 300 m/s flow continuous operation	24 GW/m^3 (24 kw/cm^3)	Yu et al (2002)
Direct current glow discharge with 2,000 K preheated air continuous operation	5 GW/m^3 (5 kw/cm^3)	Stark and Schoenbach (2001)
Electron beam source with ambient air Air temperature increases to 369 K 10 μs duration	7 GW/m^3 (7 kw/cm^3)	Vidmar and Stalder (2004)

Data: Electron density, n_e. Additional power to heat sea level air to 2,000 K in a 300 m/s flow is 10.5 GW/m^3 (10.5 kW/cm^3)

The power required remains high even for the current research. The approach, however, produces a relatively low-temperature plasma compared to the references cited. A more comprehensive set of graphs of power versus altitude for $n_e = 10^{10}$ cm^{-3} and 10^{13} cm^{-3} appear in Vidmar and Stalder (2004). The power per unit volume decreases substantially as a function of altitude, exhibits a stronger dependence on E/N, and develops a broad minimization in power for $E/N \approx 10^{-17}$ V-cm^2.

E. Excited State Concentrations

One of the results in Vidmar and Stalder (2004) is a graph of excited state species at 30,000 ft for an electron concentration of 10^{13} cm^{-3}. The simulation is for 1 ms and illustrates the build-up of excited states as a function of time. The concentration of $O_2(a^1\Delta_g)$, $O_2(v=1)$, and $O_2(v=2)$ build-up to 4×10^{15} cm^{-3}, 1×10^{17} cm^{-3}, and 3×10^{16} cm^{-3} respectively, whereas the concentration of ground state $O_2(v=0)$ falls from 2×10^{18} cm^{-3} to 2×10^{17} cm^{-3}. At the end of 1 ms of ionization, the relative concentrations of $O_2(v=0)$: $O_2(v=1)$: $O_2(v=2)$: $O_2(a^1\Delta_g)$ are 50: 25: 7.5: 1. The relatively high concentrations of $O_2(v=1)$, $O_2(v=2)$, and $O_2(a^1\Delta_g)$ indicate that excited state concentration are of sufficient magnitude to influence the overall attachment rate and net power expenditure.

The result in Fig. 4 quantifies species concentrations of interest to biological applications. Monatomic oxygen, O, for example, is a highly reactive species that can permeate through biological materials and is harmful to a cell. The simulation in Fig. 4 is for an electron concentration of 10^{10} cm^{-3} and continuous ionization for 1 ms. The concentration of O peaks at 6×10^{13} cm^{-3}, which corresponds to 2.4 ppm. O_3 and OH are also bio-reactive species with peak concentrations of 117 ppm. The concentrations in Fig. 4 all exhibits a peak with a dip to the left due to the inflection due to three-body attachment of electrons to oxygen and a substantial shift in electron energy due to water vapor in the air at sea level.

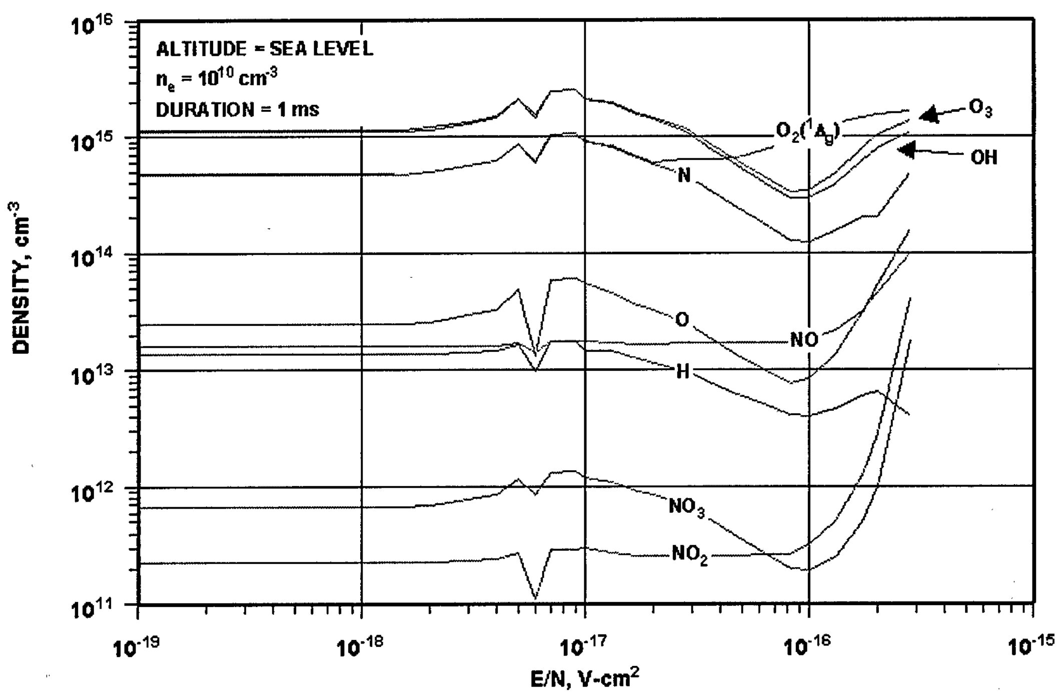


Figure 4 Species concentrations for biological applications.

Another technological area that may benefit from the air plasma research is the complex air chemistry associated with naturally occurring lightning and thundercloud discharges. Chubenko *et al* (2003) describes an experiment and results that quantify high-energy electron and X-ray production in clouds prior to breakdown. The mechanism for high energy electrons described by Babich *et al* (1998) and Gurevich *et al* (1999) involves cosmic ray ionization and runaway electrons. The method proposed by Babich and Gurevich depends on the electron attachment rate and the electron momentum transfer collision rate. Dwyer (2003) analyzes a fundamental limit on the electric field in air but does not address the issue of electron attachment in air with substantial excited-state populations. It is advanced that air subject to a strong electric field for less than 1 s prior to breakdown can lead to a gas-kinetic system dominated by excited-state oxygen. The attachment rate in all likelihood will decrease but it is not known what the effect of excited states would be on electron momentum transfer. Excited-state plasma may play some role in explaining the breakdown potential in air and the anomalous observations of high-energy electrons and X-rays prior to breakdown in clouds.

IV PERSONNEL, INTERACTIONS, AND PUBLICATIONS

Personnel. The primary personnel on this project has been

- Robert J Vidmar, Principal Investigator
- Kenneth R Stalder, Consultant

Interactions. The research conducted on this project has been presented at the 55th and 56th Gaseous Electronic Conferences, and at the 2003 and 2004 American Institute of Aeronautics and Astronautics Conference in Reno Nevada. There were numerous interactions at these conferences with representatives from DoD Laboratories, National Laboratories, private companies, and Universities from around the world.

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Vidmar, R, and K Stalder, "Air Chemistry and Power to Sustain Air Plasma Generated by Electron-Beam Excitation", Oral Presentation XF2-5, 55th Gaseous Electronics Conference, 15-18 Oct, 2002, Bulletin of the American Physical Society, Vol 47, No 7, p 74, Oct, 2002

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Vidmar, R. J., and K. R. Stalder, "Air Chemistry and Power to Generate and Sustain Plasma: Plasma Lifetime Calculations," AIAA 2003-1189, p 8, Jan, 2003.

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APPENDIX

AIR-CHEMISTRY CODE: SPECIES

TYPE	NUMBER	SPECIES
NEUTRAL	14	H, He, N, O $N_2(v=0)$, $O_2(v=0)$, NO, OH O_3, CO_2, H_2O, N_2O, NO_2, NO_3
EXCITED	15	$He(^3S_1)$ $N(^2P^o)$, $N(^2D^o)$ $O(^1S)$, $O(^1D)$ $O_2(a^1\Delta_g)$, $O_2(b^1\Sigma_g^+)$ $N_2(v=1)$, $N_2(v=2)$, $N_2(v=3)$, $N_2(v=4)$ $O_2(v=1)$, $O_2(v=2)$, $O_2(v=3)$, $O_2(v=4)$
NEGATIVE	15	e O^-, O_2^-, O_3^-, O_4^- CO_3^-, CO_4^- $O_2^- \bullet H_2O$ $CO_3^- \bullet H_2O$, $CO_4^- \bullet H_2O$ NO^-, NO_2^-, NO_3^-, $NO_2^- \bullet H_2O$, $NO_3^- \bullet H_2O$
POSITIVE	14	He^+, He_2^+ N^+, N_2^+, N_4^+ O^+, O_2^+, O_4^+ H_2O^+, H_3O^+ NO^+ $O_2^+ \bullet H_2O$ $H_3O^+ \bullet H_2O$, $H_3O^+ \bullet OH$
TOTAL	58	

NEGATIVE-ION PROPERTIES

SPECIES	ELECTRON AFFINITY eV	DISSOCIATION eV	PRODUCTS
O^-	1.478	NA	
O_2^-	0.429	4.066	$O^- - O$
O_3^-	2.1	1.7	$O^- - O_2$
O_4^-	1.0	0.54	$O_2^- - O_2$
CO_3^-	3.3	1.8	$O^- - CO_2$
CO_4^-	1.2	0.8	$O_2^- - CO_2$
$O_2^- \bullet H_2O$	1.2	0.8	$O_2^- - H_2O$
$CO_3^- \bullet H_2O$	-	-	-
$CO_4^- \bullet H_2O$	-	-	-
NO^-	0.020	5.049	$N - O^-$
NO_2^-	2.38	4.1	$NO - O^-$
NO_3^-	3.9	2.5	$O_2^- - NO$
		3.5	$O^- - NO_2$
$NO_2^- \bullet H_2O$	-	-	-
$NO_3^- \bullet H_2O$	-	-	-

POSITIVE-ION PROPERTIES

SPECIES	IONIZATION eV	DISSOCIATION eV	PRODUCTS
He^+	54.4	NA	
He_2^+	NA	3.1	$He - He^+$
N^+	29.601	NA	
O^+	35.117	NA	
H_2O^+	12.619	5.84	$H - OH^+$
H_3O^+	NA	-	
NO^+	30.5	10.857	$N - O^+$
N_2^+	27.1	8.711	$N - N^+$
O_2^+	24.2	6.670	$O - O^+$
$H_3O^+ \bullet OH$	NA	1.03	$H_3O^+ - OH$
$H_3O^+ \bullet H_2O$	NA	1.37	$H_3O^+ - H_2O$
$O_2^+ \bullet H_2O$	NA	0.7	$O_2^+ - H_2O$
N_4^+	NA	0.99	$N_2 - N_2^+$
O_4^+	NA	0.41	$O_2 - O_2^+$

NEUTRAL AND EXCITED-STATE PROPERTIES

SPECIES	IONIZATION	DISSOCIATION		SPECIES	ENERGY LEVEL
	eV	eV	Products		eV
H	13.598		NA	$N_2(v=1)$	0.2888
He	24.586		NA	$N_2(v=2)$	0.5776
N	14.534		NA	$N_2(v=3)$	0.8664
O	13.618		NA	$N_2(v=4)$	1.155
N_2	15.580	9.759	N – N	$O_2(v=1)$	0.193
O_2	12.063	5.115	O – O	$O_2(v=2)$	0.386
NO	9.267	6.507	N – O	$O_2(v=3)$	0.579
OH	12.94	4.395	O – H	$O_2(v=4)$	0.772
O_3	12.80	1.051	O_2 – O	$N(^2D^o)$	2.3839
CO_2	13.769	5.453	CO – O	$N(^2P^o)$	3.5755
H_2O	12.619	5.116	H – OH	$O(^1D)$	1.9673
N_2O	12.894	1.677	N_2 – O	$O(^1S)$	4.1896
NO_2	9.78	3.116	NO – O	$O_2(a^1\Delta_g)$	0.9773
NO_3	-	2.17	NO_2 – O	$O_2(b^1\Sigma_g^+)$	1.6267
				$He(^3S_1)$	19.819

A. NEGATIVE-SPECIES REACTIONS: e

NUMBER	REACTION 12-10 size define	REACTION RATE	REFERENCE
A1	$e + O_2 \rightarrow O^- + O$	Table	Masek *et al*, 1978
A2	$e + O_3 \rightarrow O^- + O_2$	9.0×10^{-12} cm^3/s	DNA, 1979, p 24-16
A3	$e + O_2 + O_2 \rightarrow O_2^- + O_2$	Graphs	McCorket et al, 1972 Fiquet-Fayard, 1975 Alexsandrov, 1993
A4	$e + O_2 + N_2 \rightarrow O_2^- + N_2$	1.0×10^{-31} cm^6/s	DNA, 1979, p 24-14
A5	$e + O_2 + H_2O \rightarrow O_2^- + H_2O$	1.4×10^{-29} cm^6/s	DNA, 1979, p 24-14
A6	$e + O_2 + CO_2 \rightarrow O_2^- + CO_2$	3.3×10^{-30} cm^6/s	DNA, 1979, p 24-14
A7	$e + O_2 + He \rightarrow O_2^- + He$	1.0×10^{-31} cm^6/s	DNA, 1979, p 24-14 Like N_2
A132	$e + He(^3S_1) \rightarrow He + e$	$7.0 \times 10^{-10} \left(\frac{T_e}{300}\right)^{1/2}$ cm^3/s Cheret and Lambert, 1971	
A135	$e + O^- \rightarrow e + e + O$	Table	Masek *et al*, 1978

A. NEGATIVE-SPECIES REACTIONS: O^-

NUMBER	REACTION	REACTION RATE	REFERENCE
A8	$O^- + O \rightarrow O_2 + e$	2.0×10^{-10} cm^3/s	DNA, 1979, p 24-16
A9	$O^- + N \rightarrow NO + e$	5.0×10^{-10} cm^3/s	Smirnov *et al*, 2002
A10	$O^- + O_2 \rightarrow O_3 + e$	5.0×10^{-15} cm^3/s	DNA, 1979, p 24-16
A11	$O^- + O_2(a^1\Delta_g) \rightarrow O_3 + e$	3.0×10^{-10} cm^3/s	DNA, 1979, p 24-17
A12	$O^- + O_2(a^1\Delta_g) \rightarrow O_2^- + O$	1.0×10^{-10} cm^3/s	DNA, 1979, p 24-26
A13	$O^- + O_3 \rightarrow O_3^- + O$	5.3×10^{-10} cm^3/s	DNA, 1979, p 24-26
A14	$O^- + N_2 \rightarrow N_2O + e$	1.0×10^{-14} cm^3/s	DNA, 1979, p 24-17

A15	$O^- + NO \rightarrow NO_2 + e$	$2.5 \times 10^{-10} \left(\frac{300}{T_e}\right)^{0.8}$ cm^3/s	DNA, 1979, p 24-17
A16	$O^- + O_2 + O_2 \rightarrow O_3^- + O_2$	$1.1 \times 10^{-30} \left(\frac{300}{T_{air}}\right)$ cm^6/s	DNA, 1979, p 24-39
A17	$O^- + O_2 + CO_2 \rightarrow CO_3^- + O_2$	$3.1 \times 10^{-28} \left(\frac{300}{T_{air}}\right)$ cm^6/s	DNA, 1979, p 24-39
A18	$O^- + O_2 + He \rightarrow O_3^- + He$	$1.1 \times 10^{-30} \left(\frac{300}{T_{air}}\right)$ cm^6/s	DNA, 1979, p 24-39
A64	$O^- + O_2(b^1\Sigma_g^+) \rightarrow O + O_2 + e$	6.9×10^{-10} cm^3/s	Aleksandrov, 1978
A76	$O^- + O(^1D) \rightarrow O + O + e$	1.0×10^{-10} cm^3/s	Estimate
A89	$O^- + N(^2D^o) \rightarrow O + N + e$	1.0×10^{-10} cm^3/s	Estimate
A105	$O^- + N(^2P^o) \rightarrow O + N + e$	1.0×10^{-10} cm^3/s	Estimate
A122	$O^- + O(^1S) \rightarrow O + O + e$	1.0×10^{-10} cm^3/s	Estimate
A123	$O^- + He(^3S_1) \rightarrow O + He + e$	3.0×10^{-10} cm^3/s	Estimate
A142	$O^- + N_2O \rightarrow NO^- + NO$	2.0×10^{-10} cm^3/s	TR-H-78-1, p 1405
A154	$O^- + NO_2 \rightarrow NO_2^- + O$	1.0×10^{-9} cm^3/s	TR-H-78-1, p 1405
A161	$O^- + NO_3 \rightarrow NO_3^- + O$	5.0×10^{-10} cm^3/s	DNA, 1979, p 24-26

A. NEGATIVE-SPECIES REACTIONS: O_2^-

NUMBER	REACTION	REACTION RATE	REFERENCE
A19	$O_2^- + O \rightarrow O^- + O_2$	1.5×10^{-10} cm^3/s	DNA, 1979, p 24-26
A20	$O_2^- + N \rightarrow NO_2 + e$	4.0×10^{-10} cm^3/s	TR-H-78-1, p 1405
A21	$O_2^- + N \rightarrow O^- + NO$	1.0×10^{-10} cm^3/s	DNA, 1979, p 24-28
A22	$O_2^- + O_2 \rightarrow O_2 + O_2 + e$	Formulation Graphs	Pack and Phelps, 1966 Goodson *et al*, 1974
A23	$O_2^- + O_2(a^1\Delta_g) \rightarrow O_2 + O_2 + e$	2.0×10^{-10} cm^3/s	DNA, 1979, p 24-15
A124	$O_2^- + He(^3S_1) \rightarrow O_2 + He + e$	3.0×10^{-10} cm^3/s	Estimate
A24	$O_2^- + O_3 \rightarrow O_3^- + O_2$	4.0×10^{-10} cm^3/s	DNA, 1979, p 24-17
A25	$O_2^- + N_2 \rightarrow O_2 + N_2 + e$	Graph	Aleksandrov, 1980.
A26	$O_2^- + O_2 + O_2 \rightarrow O_4^- + O_2$	$3.5 \times 10^{-31} \left(\frac{300}{T_{air}}\right)$ cm^6/s	DNA, 1979, p 24-39
A27	$O_2^- + O_2 + H_2O \rightarrow O_2^- \bullet H_2O + O_2$	$3.0 \times 10^{-28} \left(\frac{300}{T_{air}}\right)$ cm^6/s	DNA, 1979, p 24-39
A28	$O_2^- + O_2 + CO_2 \rightarrow CO_4^- + O_2$	$2.0 \times 10^{-29} \left(\frac{300}{T_{air}}\right)$ cm^6/s	DNA, 1979, p 24-39
A29	$O_2^- + O_2 + He \rightarrow O_4^- + He$	$3.5 \times 10^{-31} \left(\frac{300}{T_{air}}\right)$ cm^6/s	DNA, 1979, p 24-39
A63	$O_2^- + O_2(b^1\Sigma_g^+) \rightarrow O_2 + O_2 + e$	3.6×10^{-10} cm^3/s	Aleksandrov, 1978
A75	$O_2^- + O(^1D) \rightarrow O_2 + O + e$	1.0×10^{-10} cm^3/s	Estimated
A88	$O_2^- + N(^2D^o) \rightarrow O_2 + N + e$	1.0×10^{-10} cm^3/s	Estimated
A104	$O_2^- + N(^2P^o) \rightarrow O_2 + N + e$	1.0×10^{-10} cm^3/s	Estimated

A120	$O_2^- + O(^1S) \rightarrow O^- + O + O$	1.0×10^{-10} cm^3/s	Estimated
A121	$O_2^- + O(^1S) \rightarrow O_2 + O + e$	1.0×10^{-10} cm^3/s	Estimated
A155	$O_2^- + NO_2 \rightarrow NO_2^- + O_2$	7.0×10^{-10} cm^3/s	TR-H-78-1, p 1405
A162	$O_2^- + NO_3 \rightarrow NO_3^- + O_2$	5.0×10^{-10} cm^3/s	DNA, 1979, p 24-27

A. NEGATIVE-SPECIES REACTIONS: O_3^-

NUMBER	REACTION	REACTION RATE	REFERENCE
A30	$O_3^- + O \rightarrow O_2 + O_2 + e$	1.0×10^{-11} cm^3/s	DNA, 1979, p 24-17
A31	$O_3^- + O \rightarrow O_2^- + O_2$	3.2×10^{-10} cm^3/s	DNA, 1979, p 24-29
A32	$O_3^- + CO_2 \rightarrow CO_3^- + O_2$	$5.5 \times 10^{-10} \left(\frac{300}{T_{air}}\right)^{0.49}$ cm^3/s	DNA, 1979, p 24-29
A54	$O_3^- + O_2(b^1\Sigma_g^+) \rightarrow O^- + O_2 + O_2$	1.0×10^{-10} cm^3/s	Estimate
A65	$O_3^- + O(^1D) \rightarrow O^- + O_2 + O$	1.0×10^{-10} cm^3/s	Estimate
A77	$O_3^- + N(^2D^o) \rightarrow O^- + O_2 + N$	1.0×10^{-10} cm^3/s	Estimate
A78	$O_3^- + N(^2D^o) \rightarrow O_3 + N + e$	1.0×10^{-10} cm^3/s	Estimate
A90	$O_3^- + N(^2P^o) \rightarrow O^- + O_2 + N$	1.0×10^{-10} cm^3/s	Estimate
A91	$O_3^- + N(^2P^o) \rightarrow O_2^- + O + N$	1.0×10^{-10} cm^3/s	Estimate
A92	$O_3^- + N(^2P^o) \rightarrow O_3 + N + e$	1.0×10^{-10} cm^3/s	Estimate
A106	$O_3^- + O(^1S) \rightarrow O^- + O_2 + O$	1.0×10^{-10} cm^3/s	Estimate
A107	$O_3^- + O(^1S) \rightarrow O_2^- + O + O$	1.0×10^{-10} cm^3/s	Estimate
A108	$O_3^- + O(^1S) \rightarrow O_3 + O + e$	1.0×10^{-10} cm^3/s	Estimate
A125	$O_3^- + He(^3S_1) \rightarrow O_2 + O + He + e$	3.0×10^{-10} cm^3/s	Estimate
A158	$O_3^- + NO_2 \rightarrow NO_3^- + O_2$	2.8×10^{-10} cm^3/s	TR-H-78-1, p 1406

A160	$O_3^- + NO \rightarrow NO_2^- + O_2$	$2.8 \times 10^{-12} \left(\frac{300}{T_{air}}\right)^{1.8}$ cm^3/s	DNA, 1979, p 24-27
A163	$O_3^- + NO_2 \rightarrow NO_2^- + O_3$	2.8×10^{-10} cm^3/s	DNA, 1979, p 24-27
A164	$O_3^- + NO_3 \rightarrow NO_3^- + O_3$	5.0×10^{-10} cm^3/s	DNA, 1979, p 24-27

A. NEGATIVE-SPECIES REACTIONS: O_4^-

NUMBER	REACTION	REACTION RATE	REFERENCE
A33	$O_4^- + O \rightarrow O_3^- + O_2$	4.0×10^{-10} cm^3/s	DNA, 1979, p 24-30
A34	$O_4^- + O_2 \rightarrow O_2^- + O_2 + O_2$	$2.2 \times 10^{-5} \left(\frac{300}{T_{air}}\right)^{1.8} \exp\left(-\frac{6300}{T_{air}}\right)$ cm^3/s	DNA, 1979, p 24-40
A35	$O_4^- + O_3 \rightarrow O_3^- + O_2 + O_2$	3.0×10^{-10} cm^3/s	DNA, 1979, p 24-27
A36	$O_4^- + CO_2 \rightarrow CO_4^- + O_2$	4.3×10^{-10} cm^3/s	DNA, 1979, p 24-30
A37	$O_4^- + H_2O \rightarrow O_2^- \bullet H_2O + O_2$	1.4×10^{-9} cm^3/s	DNA, 1979, p 24-30
A49	$O_4^- + O_2(a^1\Delta_g) \rightarrow O_2^- + O_2 + O_2$	1.0×10^{-10} cm^3/s	Estimate
A59	$O_4^- + O_2(b^1\Sigma_g^+) \rightarrow O_2^- + O_2 + O_2$	1.0×10^{-10} cm^3/s	Estimate
A60	$O_4^- + O_2(b^1\Sigma_g^+) \rightarrow O_2 + O_2 + O_2 + e$	1.0×10^{-10} cm^3/s	Estimate
A71	$O_4^- + O(^1D) \rightarrow O_2^- + O_2 + O$	1.0×10^{-10} cm^3/s	Estimate
A72	$O_4^- + O(^1D) \rightarrow O_2 + O_2 + O + e$	1.0×10^{-10} cm^3/s	Estimate
A84	$O_4^- + N(^2D^o) \rightarrow O_2^- + O_2 + N$	1.0×10^{-10} cm^3/s	Estimate
A85	$O_4^- + N(^2D^o) \rightarrow O_2 + O_2 + N + e$	1.0×10^{-10} cm^3/s	Estimate
A99	$O_4^- + N(^2P^o) \rightarrow O_2^- + O_2 + N$	1.0×10^{-10} cm^3/s	Estimate
A100	$O_4^- + N(^2P^o) \rightarrow O_2 + O_2 + N + e$	1.0×10^{-10} cm^3/s	Estimate
A115	$O_4^- + O(^1S) \rightarrow O_2^- + O_2 + O$	1.0×10^{-10} cm^3/s	Estimate
A116	$O_4^- + O(^1S) \rightarrow O_2 + O_2 + O + e$	1.0×10^{-10} cm^3/s	Estimate

A126	$O_4^- + He(^3S_1) \rightarrow O_2 + O_2 + He + e$	3.0×10^{-10} cm³/s	Estimate
A159	$O_4^- + NO \rightarrow NO_3^- + O_2$	2.5×10^{-10} cm³/s	TR-H-78-1, p 1407
A166	$O_4^- + NO_2 \rightarrow NO_2^- + O_2 + O_2$	5.0×10^{-10} cm³/s	DNA, 1979, p 24-27
A167	$O_4^- + NO_3 \rightarrow NO_3^- + O_2 + O_2$	5.0×10^{-10} cm³/s	DNA, 1979, p 24-27

A. NEGATIVE-SPECIES REACTIONS: $O_2^- \bullet H_2O$

NUMBER	REACTION	REACTION RATE	REFERENCE
A38	$O_2^- \bullet H_2O + O_3 \rightarrow O_3^- + O_2 + H_2O$	2.3×10^{-10} cm³/s	DNA, 1979, p 24-28
A39	$O_2^- \bullet H_2O + CO_2 \rightarrow CO_4^- + H_2O$	5.8×10^{-10} cm³/s	DNA, 1979, p 24-32
A51	$O_2^- \bullet H_2O + O_2(a^1\Delta_g) \rightarrow O_2^- + H_2O + O_2$	1.0×10^{-10} cm³/s	Estimate
A55	$O_2^- \bullet H_2O + O_2(b^1\Sigma_g^+) \rightarrow O_2^- + H_2O + O_2$	1.0×10^{-10} cm³/s	Estimate
A56	$O_2^- \bullet H_2O + O_2(b^1\Sigma_g^+) \rightarrow O_2 + H_2O + O_2 + e$	1.0×10^{-10} cm³/s	Estimate
A66	$O_2^- \bullet H_2O + O(^1D) \rightarrow O_2^- + H_2O + O$	1.0×10^{-10} cm³/s	Estimate
A67	$O_2^- \bullet H_2O + O(^1D) \rightarrow O_2 + H_2O + O + e$	1.0×10^{-10} cm³/s	Estimate
A79	$O_2^- \bullet H_2O + N(^2D^o) \rightarrow O_2^- + H_2O + N$	1.0×10^{-10} cm³/s	Estimate
A80	$O_2^- \bullet H_2O + N(^2D^o) \rightarrow O_2 + H_2O + N + e$	1.0×10^{-10} cm³/s	Estimate
A93	$O_2^- \bullet H_2O + N(^2P^o) \rightarrow O_2^- + H_2O + N$	1.0×10^{-10} cm³/s	Estimate
A94	$O_2^- \bullet H_2O + N(^2P^o) \rightarrow O_2 + H_2O + N + e$	1.0×10^{-10} cm³/s	Estimate
A109	$O_2^- \bullet H_2O + O(^1S) \rightarrow O_2^- + H_2O + O$	1.0×10^{-10} cm³/s	Estimate
A110	$O_2^- \bullet H_2O + O(^1S) \rightarrow O_2 + H_2O + O + e$	1.0×10^{-10} cm³/s	Estimate
A127	$O_2^- \bullet H_2O + He(^3S_1) \rightarrow O_2 + H_2O + He + e$	3.0×10^{-10} cm³/s	Estimate
A156	$O_2^- \bullet H_2O + NO \rightarrow NO_3^- + H_2O$	3.1×10^{-10} cm³/s	TR-H-78-1, p 1406
A157	$O_2^- \bullet H_2O + NO_2 \rightarrow NO_2^- + H_2O + O_2$	9.0×10^{-10} cm³/s	TR-H-78-1, p 1406

A. NEGATIVE-SPECIES REACTIONS: CO_3^-

NUMBER	REACTION	REACTION RATE	REFERENCE
A40	$CO_3^- + O \rightarrow O_2^- + CO_2$	1.1×10^{-10} cm^3/s	TR-H-78-1, p 1401
A41	$CO_3^- + O_2 + H_2O \rightarrow CO_3^- \bullet H_2O + O_2$	$1.0 \times 10^{-28} \left(\frac{300}{T_{air}}\right)$ cm^6/s	DNA, 1979, p 24-39
A133	$CO_3^- + He + H_2O \rightarrow CO_3^- \bullet H_2O + He$	$1.0 \times 10^{-28} \left(\frac{300}{T_{air}}\right)$ cm^6/s	DNA, 1979, p 24-39
A68	$CO_3^- + O(^1D) \rightarrow O^- + CO_2 + O$	1.0×10^{-10} cm^3/s	Estimate
A81	$CO_3^- + N(^2D^o) \rightarrow O^- + CO_2 + N$	1.0×10^{-10} cm^3/s	Estimate
A95	$CO_3^- + N(^2P^o) \rightarrow O^- + CO_2 + N$	1.0×10^{-10} cm^3/s	Estimate
A96	$CO_3^- + N(^2P^o) \rightarrow O + CO_2 + N + e$	1.0×10^{-10} cm^3/s	Estimate
A111	$CO_3^- + O(^1S) \rightarrow O^- + CO_2 + O$	1.0×10^{-10} cm^3/s	Estimate
A112	$CO_3^- + O(^1S) \rightarrow O + CO_2 + O + e$	1.0×10^{-10} cm^3/s	Estimate
A128	$CO_3^- + He(^3S_1) \rightarrow CO_2 + O + He + e$	3.0×10^{-10} cm^3/s	Estimate
A136	$CO_3^- + NO \rightarrow NO_2^- + CO_2$	$1.1 \times 10^{-11} \left(\frac{300}{T_{air}}\right)^{1.1}$ cm^3/s	TR-H-78-1, p 1401
A137	$CO_3^- + NO_2 \rightarrow NO_3^- + CO_2$	2.0×10^{-10} cm^3/s	TR-H-78-1, p 1401
A138	$CO_3^- + O_2 \rightarrow O_3^- + CO_2$	6.0×10^{-15} cm^3/s	TR-H-78-1, p 1401
A169	$CO_3^- + NO_3 \rightarrow NO_3^- + CO_2 + O$	5.0×10^{-10} cm^3/s	DNA, 1979, p 24-27

A. NEGATIVE-SPECIES REACTIONS: CO_4^-

NUMBER	REACTION	REACTION RATE	REFERENCE
A42	$CO_4^- + O \rightarrow CO_3^- + O_2$	1.5×10^{-10} cm³/s	DNA, 1979, p 24-31
A43	$CO_4^- + O_2 \rightarrow O_4^- + CO_2$	$4.3 \times 10^{-10} \exp\left(-\frac{3000}{T_{air}}\right)$ cm³/s	DNA, 1979, p 24-31
A44	$CO_4^- + O_3 \rightarrow O_3^- + CO_2 + O_2$	1.3×10^{-10} cm³/s	DNA, 1979, p 24-28
A45	$CO_4^- + N_2 + H_2O \rightarrow CO_4^- \bullet H_2O + N_2$	$5.0 \times 10^{-29} \left(\frac{300}{T_{air}}\right)$ cm⁶/s	DNA, 1979, p 24-39
A134	$CO_4^- + He + H_2O \rightarrow CO_4^- \bullet H_2O + He$	$5.0 \times 10^{-29} \left(\frac{300}{T_{air}}\right)$ cm⁶/s	DNA, 1979, p 24-39
A46	$CO_4^- + H_2O \rightarrow O_2^- \bullet H_2O + CO_2$	2.0×10^{-10} cm³/s	Estimate
A50	$CO_4^- + O_2(a^1\Delta_g) \rightarrow O_2^- + CO_2 + O_2$	1.0×10^{-10} cm³/s	Estimate
A57	$CO_4^- + O_2(b^1\Sigma_g^+) \rightarrow O_2^- + CO_2 + O_2$	1.0×10^{-10} cm³/s	Estimate
A58	$CO_4^- + O_2(b^1\Sigma_g^+) \rightarrow O_2 + CO_2 + O_2 + e$	1.0×10^{-10} cm³/s	Estimate
A69	$CO_4^- + O(^1D) \rightarrow O_2^- + CO_2 + O$	1.0×10^{-10} cm³/s	Estimate
A70	$CO_4^- + O(^1D) \rightarrow O_2 + CO_2 + O + e$	1.0×10^{-10} cm³/s	Estimate
A113	$CO_4^- + O(^1S) \rightarrow O_2^- + CO_2 + O$	1.0×10^{-10} cm³/s	Estimate
A114	$CO_4^- + O(^1S) \rightarrow O_2 + CO_2 + O + e$	1.0×10^{-10} cm³/s	Estimate
A82	$CO_4^- + N(^2D^o) \rightarrow O_2^- + CO_2 + N$	1.0×10^{-10} cm³/s	Estimate
A83	$CO_4^- + N(^2D^o) \rightarrow O_2 + CO_2 + N + e$	1.0×10^{-10} cm³/s	Estimate
A97	$CO_4^- + N(^2P^o) \rightarrow O_2^- + CO_2 + N$	1.0×10^{-10} cm³/s	Estimate
A98	$CO_4^- + N(^2P^o) \rightarrow O_2 + CO_2 + N + e$	1.0×10^{-10} cm³/s	Estimate
A129	$CO_4^- + He(^3S_1) \rightarrow CO_2 + O_2 + He + e$	3.0×10^{-10} cm³/s	Estimate
A141	$CO_4^- + NO \rightarrow NO_3^- + CO_2$	4.8×10^{-11} cm³/s	TR-H-78-1, p 1401
A170	$CO_4^- + NO_3 \rightarrow NO_3^- + CO_2 + O_2$	5.0×10^{-10} cm³/s	DNA, 1979, p 24-28

A. NEGATIVE-SPECIES REACTIONS: $CO_3^- \bullet H_2O$

NUMBER	REACTION	REACTION RATE	REFERENCE
A47	$CO_3^- \bullet H_2O + N_2 \rightarrow CO_3^- + H_2O + N_2$	1.0×10^{-14} cm^3/s	Estimate
A52	$CO_3^- \bullet H_2O + O_2(a^1\Delta_g) \rightarrow CO_3^- + H_2O + O_2$	1.0×10^{-10} cm^3/s	Estimate
A61	$CO_3^- \bullet H_2O + O_2(b^1\Sigma_g^+) \rightarrow CO_3^- + H_2O + O_2$	1.0×10^{-10} cm^3/s	Estimate
A73	$CO_3^- \bullet H_2O + O(^1D) \rightarrow CO_3^- + H_2O + O$	1.0×10^{-10} cm^3/s	Estimate
A86	$CO_3^- \bullet H_2O + N(^2D^o) \rightarrow CO_3^- + H_2O + N$	1.0×10^{-10} cm^3/s	Estimate
A101	$CO_3^- \bullet H_2O + N(^2P^o) \rightarrow CO_3^- + H_2O + N$	1.0×10^{-10} cm^3/s	Estimate
A102	$CO_3^- \bullet H_2O + N(^2P^o) \rightarrow CO_2 + H_2O + N + O + e$	1.0×10^{-10} cm^3/s	Estimate
A117	$CO_3^- \bullet H_2O + O(^1S) \rightarrow CO_3^- + H_2O + O$	1.0×10^{-10} cm^3/s	Estimate
A118	$CO_3^- \bullet H_2O + O(^1S) \rightarrow CO_2 + H_2O + O + O + e$	1.0×10^{-10} cm^3/s	Estimate
A130	$CO_3^- \bullet H_2O + He(^3S_1) \rightarrow CO_2 + O + H_2O + He + e$	3.0×10^{-10} cm^3/s	Estimate
A139	$CO_3^- \bullet H_2O + NO \rightarrow NO_2^- + H_2O + CO_2$	7.0×10^{-12} cm^3/s	TR-H-78-1, p 1401
A140	$CO_3^- \bullet H_2O + NO_2 \rightarrow NO_3^- + H_2O + CO_2$	1.5×10^{-10} cm^3/s	TR-H-78-1, p 1401
A173	$CO_3^- \bullet H_2O + NO \rightarrow NO_2^- \bullet H_2O + CO_2$	7.0×10^{-12} cm^3/s	DNA, 1979, p 24-32

A. NEGATIVE-SPECIES REACTIONS: $CO_4^- \bullet H_2O$

NUMBER	REACTION	REACTION RATE	REFERENCE
A48	$CO_4^- \bullet H_2O + N_2 \rightarrow CO_4^- + H_2O + N_2$	3.0×10^{-14} cm³/s	Estimate
A53	$CO_4^- \bullet H_2O + O_2(a^1\Delta_g) \rightarrow CO_4^- + H_2O + O_2$	1.0×10^{-10} cm³/s	Estimate
A62	$CO_4^- \bullet H_2O + O_2(b^1\Sigma_g^+) \rightarrow CO_4^- + H_2O + O_2$	1.0×10^{-10} cm³/s	Estimate
A74	$CO_4^- \bullet H_2O + O(^1D) \rightarrow CO_4^- + H_2O + O$	1.0×10^{-10} cm³/s	Estimate
A87	$CO_4^- \bullet H_2O + N(^2D^o) \rightarrow CO_4^- + H_2O + N$	1.0×10^{-10} cm³/s	Estimate
A103	$CO_4^- \bullet H_2O + N(^2P^o) \rightarrow CO_4^- + H_2O + N$	1.0×10^{-10} cm³/s	Estimate
A119	$CO_4^- \bullet H_2O + O(^1S) \rightarrow CO_4^- + H_2O + O$	1.0×10^{-10} cm³/s	Estimate
A131	$CO_4^- \bullet H_2O + He(^3S_1) \rightarrow CO_2 + O_2 + H_2O + He + e$	3.0×10^{-10} cm³/s	Estimate
A174	$CO_4^- \bullet H_2O + NO \rightarrow NO_3^- \bullet H_2O + CO_2$	1.0×10^{-11} cm³/s	DNA, 1979, p 24-32

A. NEGATIVE-SPECIES REACTIONS: NO^-

NUMBER	REACTION	REACTION RATE	
A143	$NO^- + He \rightarrow NO + He + e$	2.4×10^{-13} cm³/s	TR-H-78-1, p 1403
A144	$NO^- + CO_2 \rightarrow NO + CO_2 + e$	8.3×10^{-12} cm³/s	TR-H-78-1, p 1403
A145	$NO^- + NO \rightarrow NO + NO + e$	5.0×10^{-12} cm³/s	TR-H-78-1, p 1404
A146	$NO^- + NO_2 \rightarrow NO_2^- + NO$	7.4×10^{-10} cm³/s	TR-H-78-1, p 1404
A147	$NO^- + N_2O \rightarrow NO + N_2O + e$	5.1×10^{-12} cm³/s	TR-H-78-1, p 1404
A148	$NO^- + O_2 \rightarrow O_2^- + NO$	5.0×10^{-10} cm³/s	TR-H-78-1, p 1404

A. NEGATIVE-SPECIES REACTIONS: NO_2^-

NUMBER	REACTION	REACTION RATE	REFERENCE
A149	$NO_2^- + H_2O + O_2 \rightarrow NO_2^- \bullet H_2O + O_2$	1.6×10^{-28} cm^6/s	TR-H-78-1, p 1404
A150	$NO_2^- + NO_2 \rightarrow NO_3^- + NO$	3.0×10^{-13} cm^3/s	TR-H-78-1, p 1404
A151	$NO_2^- + O_3 \rightarrow NO_3^- + O_2$	1.2×10^{-10} cm^3/s	TR-H-78-1, p 1404
A165	$NO_2^- + NO_3 \rightarrow NO_3^- + NO_2$	5.0×10^{-10} cm^3/s	DNA, 1979, p 24-27
A171	$NO_2^- + N_2O \rightarrow NO_3^- + N_2$	1.0×10^{-12} cm^3/s	DNA, 1979, p 24-30
A175	$NO_2^- + H_2O + NO \rightarrow NO_2^- \bullet H_2O + NO$	$1.3 \times 10^{-28} \left(\frac{300}{T_{air}}\right)^{1.0}$ cm^6/s	
	Albritton, p 77		DNA, 1979, p 24-39

A. NEGATIVE-SPECIES REACTIONS: NO_3^-, $NO_2^- \bullet H_2O$

NUMBER	REACTION	REACTION RATE	REFERENCE
A152	$NO_3^- + NO \rightarrow NO_2^- + NO_2$	1.0×10^{-12} cm^3/s	TR-H-78-1, p 1404
A153	$NO_3^- + O \rightarrow NO_2 + O_2 + e$	1.0×10^{-11} cm^3/s	TR-H-78-1, p 1404
A168	$NO_3^- + NO_3 \rightarrow NO_3^- + NO + O_2$	5.0×10^{-10} cm^3/s	DNA, 1979, p 24-27
A172	$NO_2^- \bullet H_2O + O_3 \rightarrow NO_3^- \bullet H_2O + O_2$	1.0×10^{-11} cm^3/s	DNA, 1979, p 24-32
A176	$NO_2^- \bullet H_2O + O_2 \rightarrow NO_2^- + H_2O + O_2$	5.0×10^{-15} cm^3/s	Albritton, 1978

B. POSITIVE-SPECIES REACTIONS: N^+, N_2^+

NUMBER	REACTION	REACTION RATE	REFERENCE
B1	$N^+ + O_2 \rightarrow N + O_2^+$	2.8×10^{-10} cm³/s	DNA, 1979, p 24-18
B2	$N^+ + O_2 \rightarrow NO^+ + O$	2.8×10^{-10} cm³/s	DNA, 1979, p 24-22
B3	$N^+ + H_2O \rightarrow H_2O^+ + N$	2.6×10^{-9} cm³/s	DNA, 1979, p 24-18
B4	$N_2^+ + O \rightarrow NO^+ + N$	$1.3 \times 10^{-10} \left(\frac{300}{T_{air}}\right)^{0.46}$ cm³/s	DNA, 1979, p 24-23
B5	$N_2^+ + N_2 + N_2 \rightarrow N_4^+ + N_2$	$5.0 \times 10^{-29} \left(\frac{300}{T_{air}}\right)$ cm⁶/s	DNA, 1979, p 24-34
B6	$N_2^+ + N_2 + He \rightarrow N_4^+ + He$	$5.0 \times 10^{-29} \left(\frac{300}{T_{air}}\right)$ cm⁶/s	DNA, 1979, p 24-34
B64	$N_2^+ + He(^3S_1) \rightarrow N^+ + N + He$	1.0×10^{-10} cm³/s	Estimate

B. POSITIVE-SPECIES REACTIONS: N_4^+

NUMBER	REACTION	REACTION RATE	REFERENCE
B7	$N_4^+ + O_2 \rightarrow O_2^+ + N_2 + N_2$	4.0×10^{-10} cm³/s	DNA, 1979, p 24-21
B33	$N_4^+ + O_2(a^1\Delta_g) \rightarrow N_2^+ + N_2 + O_2$	1.0×10^{-10} cm³/s	Estimate
B37	$N_4^+ + O_2(b^1\Sigma_g^+) \rightarrow N_2^+ + N_2 + O_2$	1.0×10^{-10} cm³/s	Estimate
B42	$N_4^+ + O(^1D) \rightarrow N_2^+ + N_2 + O$	1.0×10^{-10} cm³/s	Estimate
B47	$N_4^+ + N(^2D^o) \rightarrow N_2^+ + N_2 + N$	1.0×10^{-10} cm³/s	Estimate
B52	$N_4^+ + N(^2P^o) \rightarrow N_2^+ + N_2 + N$	1.0×10^{-10} cm³/s	Estimate
B57	$N_4^+ + O(^1S) \rightarrow N_2^+ + N_2 + O$	1.0×10^{-10} cm³/s	Estimate
B63	$N_4^+ + He(^3S_1) \rightarrow N^+ + N + N_2 + He$	1.0×10^{-10} cm³/s	Estimate

B. POSITIVE-SPECIES REACTIONS: O^+

NUMBER	REACTION	REACTION RATE	
B8	$O^+ + O_2 \rightarrow O_2^+ + O$	$2.0 \times 10^{-11} \left(\frac{300}{T_{air}}\right)^{0.4}$ cm^3/s	DNA, 1979, p 24-18
B9	$O^+ + H_2O \rightarrow H_2O^+ + O$	2.3×10^{-9} cm^3/s	DNA, 1979, p 24-18
B10	$O^+ + N_2 + N_2 \rightarrow NO^+ + N + N_2$	$6.0 \times 10^{-29} \left(\frac{300}{T_{air}}\right)^{2}$ cm^6/s	DNA, 1979, p 24-33
B73	$O^+ + N_2 + He \rightarrow NO^+ + N + He$	$6.0 \times 10^{-29} \left(\frac{300}{T_{air}}\right)^{2}$ cm^6/s	DNA, 1979, p 24-33

B. POSITIVE-SPECIES REACTIONS: O_2^+

NUMBER	REACTION	REACTION RATE	REFERENCE
B11	$O_2^+ + N \rightarrow NO^+ + O$	1.2×10^{-10} cm^3/s	DNA, 1979, p 24-22
B12	$O_2^+ + O_2 + O_2 \rightarrow O_4^+ + O_2$	$3.9 \times 10^{-30} \left(\frac{300}{T_{air}}\right)^{3.2}$ cm^6/s	DNA, 1979, p 24-33
B13	$O_2^+ + O_2 + He \rightarrow O_4^+ + He$	$3.9 \times 10^{-30} \left(\frac{300}{T_{air}}\right)^{3.2}$ cm^6/s	DNA, 1979, p 24-33
B14	$O_2^+ + H_2O + N_2 \rightarrow O_2^+ \bullet H_2O + N_2$	$2.8 \times 10^{-28} \left(\frac{300}{T_{air}}\right)^{2}$ cm^6/s	DNA, 1979, p 24-33
B62	$O_2^+ + He(^3S_1) \rightarrow O^+ + O + He$	1.0×10^{-10} cm^3/s	Estimate

B74	$O_2^+ + H_2O + He \rightarrow O_2^+ \bullet H_2O + He$	$2.8 \times 10^{-28} \left(\frac{300}{T_{air}}\right)^2$ cm^6/s	DNA, 1979, p 24-33
B76	$O_2^+ + NO \rightarrow NO^+ + O_2$	4.4×10^{-10} cm^3/s	TR-H-78-1, p 1399

B. POSITIVE-SPECIES REACTIONS: O_4^+

NUMBER	REACTION	REACTION RATE	REFERENCE
B15	$O_4^+ + O \rightarrow O_2^+ + O_3$	3.0×10^{-10} cm^3/s	DNA, 1979, p 24-23
B16	$O_4^+ + O_2(a^1\Delta_g) \rightarrow O_2^+ + O_2 + O_2$	1.0×10^{-10} cm^3/s	DNA, 1979, p 24-21
B17	$O_4^+ + N_2 \rightarrow O_2^+ + O_2 + N_2$	$1.0 \times 10^{-5} \left(\frac{300}{T_{air}}\right)^{4.2} \exp\left(-\frac{5400}{T_{air}}\right)$ cm^3/s	DNA, 1979, p 24-36
B18	$O_4^+ + H_2O \rightarrow O_2^+ \bullet H_2O + O_2$	1.5×10^{-9} cm^3/s	DNA, 1979, p 24-23
B39	$O_4^+ + O_2(b^1\Sigma_g^+) \rightarrow O_2^+ + O_2 + O_2$	1.0×10^{-10} cm^3/s	Estimate
B44	$O_4^+ + O(^1D) \rightarrow O_2^+ + O_2 + O$	1.0×10^{-10} cm^3/s	Estimate
B49	$O_4^+ + N(^2D^o) \rightarrow O_2^+ + O_2 + N$	1.0×10^{-10} cm^3/s	Estimate
B54	$O_4^+ + N(^2P^o) \rightarrow O_2^+ + O_2 + N$	1.0×10^{-10} cm^3/s	Estimate
B59	$O_4^+ + O(^1S) \rightarrow O_2^+ + O_2 + O$	1.0×10^{-10} cm^3/s	Estimate
B61	$O_4^+ + He(^3S_1) \rightarrow O^+ + O + O_2 + He$	1.0×10^{-10} cm^3/s	Estimate

B. POSITIVE-SPECIES REACTIONS: He^+, He_2^+

NUMBER	REACTION	REACTION RATE	REFERENCE
B19	$He^+ + N_2 \rightarrow N^+ + N + He$	6.0×10^{-10} cm^3/s	DNA, 1979, p 18A-11
B20	$He^+ + N_2 \rightarrow N_2^+ + He$	6.0×10^{-10} cm^3/s	DNA, 1979, p 18A-11
B21	$He^+ + O_2 \rightarrow O^+ + O + He$	6.0×10^{-10} cm^3/s	DNA, 1979, p 18A-11
B22	$He^+ + O_2 \rightarrow O_2^+ + He$	6.0×10^{-10} cm^3/s	DNA, 1979, p 18A-11
B23	$He^+ + He + He \rightarrow He_2^+ + He$	1.1×10^{-31} cm^6/s	Delpech, 1973
B24	$He_2^+ + N_2 \rightarrow N_2^+ + He + He$	1.2×10^{-9} cm^3/s	DNA, 1979, p 18A-11
B60	$He_2^+ + O_2 \rightarrow O_2^+ + He + He$	1.2×10^{-9} cm^3/s	Estimate
B65	$He_2^+ + He(^3S_1) \rightarrow He^+ + He + He$	1.0×10^{-10} cm^3/s	Estimate

B. POSITIVE-SPECIES REACTIONS: NO^+, H_2O^+, H_3O^+

NUMBER	REACTION	REACTION RATE	REFERENCE
B68	$NO^+ + He(^3S_1) \rightarrow N^+ + O + He$	5.0×10^{-11} cm^3/s	Estimate
B71	$NO^+ + He(^3S_1) \rightarrow O^+ + N + He$	5.0×10^{-11} cm^3/s	Estimate
B29	$H_2O^+ + O_2 \rightarrow O_2^+ + H_2O$	2.0×10^{-10} cm^3/s	DNA, 1979, p 24-20
B30	$H_2O^+ + H_2O \rightarrow H_3O^+ + OH$	1.8×10^{-9} cm^3/s	DNA, 1979, p 24-23
B66	$H_2O^+ + He(^3S_1) \rightarrow O^+ + 2H + He$	1.0×10^{-10} cm^3/s	Estimate
B31	$H_3O^+ + H_2O + N_2 \rightarrow H_3O^+ \bullet H_2O + N_2$	$3.4 \times 10^{-27} \left(\frac{300}{T_{air}}\right)^4$ cm^6/s	DNA, 1979, p 24-34
B67	$H_3O^+ + He(^3S_1) \rightarrow O^+ + 3H + He$	1.0×10^{-10} cm^3/s	Estimate

B75	$H_3O^+ + H_2O + He \rightarrow H_3O^+ \bullet H_2O + He$	$3.4 \times 10^{-27} \left(\frac{300}{T_{air}}\right)^4$ cm^6/s	DNA, 1979, p 24-34

B. POSITIVE-SPECIES REACTIONS: $O_2^+ \bullet H_2O$

NUMBER	REACTION	REACTION RATE	REFERENCE
B25	$O_2^+ \bullet H_2O + O_2 \rightarrow O_4^+ + H_2O$	$2.0 \times 10^{-10} \exp\left(-\frac{2300}{T_{air}}\right)$ cm^3/s	DNA, 1979, p 24-24
B26	$O_2^+ \bullet H_2O + O_2(a^1\Delta_g) \rightarrow O_2^+ + H_2O + O_2$	1.0×10^{-10} cm^3/s	DNA, 1979, p 24-21
B27	$O_2^+ \bullet H_2O + NO \rightarrow NO^+ + H_2O + O_2$	1.0×10^{-10} cm^3/s	DNA, 1979, p 24-21
B28	$O_2^+ \bullet H_2O + H_2O \rightarrow H_3O^+ \bullet OH + O_2$	1.0×10^{-9} cm^3/s	DNA, 1979, p 24-24
B38	$O_2^+ \bullet H_2O + O_2(b^1\Sigma_g^+) \rightarrow O_2^+ + H_2O + O_2$	1.0×10^{-10} cm^3/s	Estimate
B43	$O_2^+ \bullet H_2O + O(^1D) \rightarrow O_2^+ + H_2O + O$	1.0×10^{-10} cm^3/s	Estimate
B48	$O_2^+ \bullet H_2O + N(^2D^o) \rightarrow O_2^+ + H_2O + N$	1.0×10^{-10} cm^3/s	Estimate
B53	$O_2^+ \bullet H_2O + N(^2P^o) \rightarrow O_2^+ + H_2O + N$	1.0×10^{-10} cm^3/s	Estimate
B58	$O_2^+ \bullet H_2O + O(^1S) \rightarrow O_2^+ + H_2O + O$	1.0×10^{-10} cm^3/s	Estimate
B69	$O_2^+ \bullet H_2O + He(^3S_1) \rightarrow O^+ + O + H_2O + He$	1.0×10^{-10} cm^3/s	Estimate

B. POSITIVE-SPECIES REACTIONS: $H_3O^+ \bullet OH$

NUMBER	REACTION	REACTION RATE	REFERENCE
B32	$H_3O^+ \bullet OH + H_2O \rightarrow H_3O^+ \bullet H_2O + OH$	1.4×10^{-9} cm^3/s	DNA, 1979, p 24-26
B34	$H_3O^+ \bullet OH + O_2(a^1\Delta_g) \rightarrow H_3O^+ + OH + O_2$	1.0×10^{-10} cm^3/s	Estimate
B36	$H_3O^+ \bullet OH + O_2(b^1\Sigma_g^+) \rightarrow H_3O^+ + OH + O_2$	1.0×10^{-10} cm^3/s	Estimate
B41	$H_3O^+ \bullet OH + O(^1D) \rightarrow H_3O^+ + OH + O$	1.0×10^{-10} cm^3/s	Estimate
B46	$H_3O^+ \bullet OH + N(^2D^o) \rightarrow H_3O^+ + OH + N$	1.0×10^{-10} cm^3/s	Estimate
B51	$H_3O^+ \bullet OH + N(^2P^o) \rightarrow H_3O^+ + OH + N$	1.0×10^{-10} cm^3/s	Estimate
B56	$H_3O^+ \bullet OH + O(^1S) \rightarrow H_3O^+ + OH + O$	1.0×10^{-10} cm^3/s	Estimate
B72	$H_3O^+ \bullet OH + He(^3S_1) \rightarrow O^+ + 3H + OH + He$	1.0×10^{-10} cm^3/s	Estimate

B. POSITIVE-SPECIES REACTIONS: $H_3O^+ \bullet H_2O$

NUMBER	REACTION	REACTION RATE	REFERENCE
B35	$H_3O^+ \bullet H_2O + O_2(b^1\Sigma_g^+) \rightarrow H_3O^+ + H_2O + O_2$	1.0×10^{-10} cm^3/s	Estimate
B40	$H_3O^+ \bullet H_2O + O(^1D) \rightarrow H_3O^+ + H_2O + O$	1.0×10^{-10} cm^3/s	Estimate
B45	$H_3O^+ \bullet H_2O + N(^2D^o) \rightarrow H_3O^+ + H_2O + N$	1.0×10^{-10} cm^3/s	Estimate
B50	$H_3O^+ \bullet H_2O + N(^2P^o) \rightarrow H_3O^+ + H_2O + N$	1.0×10^{-10} cm^3/s	Estimate
B55	$H_3O^+ \bullet H_2O + O(^1S) \rightarrow H_3O^+ + H_2O + O$	1.0×10^{-10} cm^3/s	Estimate
B70	$H_3O^+ \bullet H_2O + He(^3S_1) \rightarrow O^+ + 3H + H_2O + He$	1.0×10^{-10} cm^3/s	Estimate

C. NEUTRAL-SPECIES REACTIONS: H, N

NUMBER	REACTION	REACTION RATE	REFERENCE
C40	$H+NO_2 \rightarrow NO+OH$	$4.0 \times 10^{-10}\ \exp(-340/T_{air})\ cm^3/s$	JPL, 1997, p 19
C1	$N+N+N_2 \rightarrow N_2+N_2$	$7.6 \times 10^{-34}\ \exp(+500/T_{air})\ cm^6/s$	DNA, 1979, p 24-43
C31	$N+N+He \rightarrow N_2+He$	$7.6 \times 10^{-34}\ \exp(+500/T_{air})\ cm^6/s$	Estimate
C41	$N+O_2 \rightarrow NO+O$	$1.5 \times 10^{-11}\ \exp(-3600/T_{air})\ cm^3/s$	JPL, 1997, p 19
C42	$N+NO \rightarrow O+N_2$	$2.1 \times 10^{-11}\ \exp(+100/T_{air})\ cm^3/s$	JPL, 1997, p 19
C43	$N+NO_2 \rightarrow O+N_2O$	$5.8 \times 10^{-12}\ \exp(+220/T_{air})\ cm^3/s$	JPL, 1997, p 19

C. NEUTRAL-SPECIES REACTIONS: O, O(^{1}D)

NUMBER	REACTION	REACTION RATE	REFERENCE
C2	$O+O+N_2 \rightarrow O_2+N_2$	$1.3 \times 10^{-33} \left(\frac{3000}{T_{air}}\right) \exp\left(-\frac{170}{T_{air}}\right)\ cm^6/s$	DNA, 1979, p 24-42
C32	$O+O+He \rightarrow O_2+He$	$1.3 \times 10^{-33} \left(\frac{3000}{T_{air}}\right) \exp\left(-\frac{170}{T_{air}}\right)\ cm^6/s$	DNA, 1979, p 24-42
C3	$O+O_2+N_2 \rightarrow O_3+N_2$	$1.1 \times 10^{-34}\ \exp\left(+\frac{510}{T_{air}}\right)\ cm^6/s$	DNA, 1979, p 24-43
C33	$O+O_2+He \rightarrow O_3+He$	$1.1 \times 10^{-34}\ \exp\left(+\frac{510}{T_{air}}\right)\ cm^6/s$	DNA, 1979, p 24-43

C34	$O + NO + N_2 \rightarrow NO_2 + N_2$	$9.0 \times 10^{-32}\ (300/T_{air})^{1.5}\ cm^6/s$	JPL, 1997, p 123
C35	$O + NO \rightarrow NO_2$	$3.0 \times 10^{-11}\ cm^3/s$	JPL, 1997, p 123
C36	$O + NO_3 \rightarrow NO_2 + O_2$	$1.0 \times 10^{-11}\ cm^3/s$	JPL, 1997, p 18
C37	$O + NO_2 + N_2 \rightarrow NO_3 + N_2$	$9.0 \times 10^{-32}\ (300/T_{air})^{2.0}\ cm^6/s$	JPL, 1997, p 123
C38	$O + NO_2 \rightarrow NO_3$	$2.2 \times 10^{-11}\ cm^3/s$	JPL, 1997, p 123
C39	$O + NO_2 \rightarrow NO + O_2$	$6.5 \times 10^{-12}\ \exp(+120/T_{air})\ cm^3/s$	JPL, 1997, p 18

C23	$O(^1D) + N_2 \rightarrow O + N_2$	$3.0 \times 10^{-11}\ cm^3/s$	DNA, 1979, p 24-51
C24	$O(^1D) + O_2 \rightarrow O + O_2$	$4.1 \times 10^{-11}\ cm^3/s$	DNA, 1979, p 24-51
C25	$O(^1D) + H_2O \rightarrow 2OH$	$2.3 \times 10^{-10}\ cm^3/s$	Baulch *et al*, 1982

C. NEUTRAL-SPECIES REACTIONS: O_2, NO, O_3, N_2O

NUMBER	REACTION	REACTION RATE	REFERENCE
C44	$O_2 + NO + NO \rightarrow NO_2 + NO_2$	$3.3 \times 10^{-39}\ \exp(+530/T_{air})\ cm^6/s$	DNA, 1979, p 24-48
C45	$NO + O_3 \rightarrow O_2 + NO_2$	$2.0 \times 10^{-12}\ \exp(-1400/T_{air})\ cm^3/s$	JPL, 1997, p 19
C46	$NO + NO_3 \rightarrow NO_2 + NO_2$	$1.5 \times 10^{-11}\ \exp(+170/T_{air})\ cm^3/s$	JPL, 1997, p 19
C47	$O_3 + NO_2 \rightarrow O_2 + NO_3$	$1.2 \times 10^{-13}\ \exp(-2450/T_{air})\ cm^3/s$	JPL, 1997, p 19
C13	$N_2O + O(^1D) \rightarrow N_2 + O + O$	$7.0 \times 10^{-11}\ cm^3/s$	DNA, 1979, p 24-46
C14	$N_2O + O(^1D) \rightarrow 2NO$	$7.0 \times 10^{-11}\ cm^3/s$	DNA, 1979, p 24-46
C15	$N_2O + N(^2D^o) \rightarrow N_2 + N + O$	$1.0 \times 10^{-10}\ cm^3/s$	Estimate
C16	$N_2O + N(^2P^o) \rightarrow N_2 + N + O$	$1.0 \times 10^{-10}\ cm^3/s$	Estimate
C17	$N_2O + O(^1S) \rightarrow N_2 + O + O$	$1.0 \times 10^{-10}\ cm^3/s$	Estimate

C. NEUTRAL-SPECIES REACTIONS: NO_2, NO_3

NUMBER	REACTION	REACTION RATE	REFERENCE
C18	$NO_2 + N(^2P^o) \rightarrow NO + O + N$	1.0×10^{-10} cm^3/s	Estimate
C19	$NO_2 + O(^1S) \rightarrow NO + O + O$	1.0×10^{-10} cm^3/s	Estimate
C48	$NO_3 + NO_3 \rightarrow O_2 + NO_2 + NO_2$	$8.5 \times 10^{-13} \exp(-2450/T_{air})$ cm^3/s	JPL, 1997, p 19

C. NEUTRAL-SPECIES REACTIONS: $O_2(a^1\Delta_g)$, $O_2(b^1\Sigma_g^+)$, O_3

NUMBER	REACTION	REACTION RATE	REFERENCE
C4	$O_2(a^1\Delta_g) + O_2 \rightarrow O_2 + O_2$	$2.2 \times 10^{-18} \left(\frac{T_{air}}{300}\right)^{0.8}$ cm^3/s	DNA, 1979, p 24-53
C5	$O_2(a^1\Delta_g) + N_2 \rightarrow O_2 + N_2$	2.0×10^{-20} cm^3/s	DNA, 1979, p 24-53
C6	$O_2(a^1\Delta_g) + H_2O \rightarrow O_2 + H_2O$	1.5×10^{-17} cm^3/s	DNA, 1979, p 20-41
C20	$O_2(b^1\Sigma_g^+) + N_2 \rightarrow O_2 + N_2$	2.0×10^{-15} cm^3/s	DNA, 1979, p 24-53
C21	$O_2(b^1\Sigma_g^+) + O_2 \rightarrow O_2 + O_2$	1.5×10^{-16} cm^3/s	DNA, 1979, p 24-53
C22	$O_2(b^1\Sigma_g^+) + H_2O \rightarrow O_2 + H_2O$	4.0×10^{-12} cm^3/s	Baulch *et al*, 1982
C7	$O^3 + O_2(b^1\Sigma_g^+) \rightarrow O_2 + O_2 + O$	2.5×10^{-11} cm^3/s	DNA, 1979, p 24-45
C8	$O^3 + O(^1D) \rightarrow O_2 + O_2$	2.4×10^{-10} cm^3/s	DNA, 1979, p 24-46
C9	$O^3 + O(^1D) \rightarrow O_2 + O + O$	1.2×10^{-10} cm^3/s	Estimate
C10	$O^3 + N(^2D^o) \rightarrow O_2 + N + O$	1.0×10^{-10} cm^3/s	Estimate
C11	$O^3 + N(^2P^o) \rightarrow O_2 + N + O$	1.0×10^{-10} cm^3/s	Estimate

C12	$O^3 + O(^1S) \rightarrow O_2 + O + O$	1.0×10^{-10} cm^3/s	Estimate

C. NEUTRAL-SPECIES REACTIONS: $He(^3S_1)$

NUMBER	REACTION	REACTION RATE	REFERENCE
C26	$He(^3S_1) + He(^3S_1) \rightarrow He_2^+ + e$	2.0×10^{-9} cm^3/s	Cheret and Lambert, 1971
C27	$He(^3S_1) + He(^3S_1) \rightarrow He^+ + He + e$	2.0×10^{-9} cm^3/s	Cheret and Lambert, 1971
C28	$He(^3S_1) + N_2 \rightarrow N^+ + N + He + e$	1.0×10^{-10} cm^3/s	Estimate
C29	$He(^3S_1) + O_2 \rightarrow O^+ + O + He + e$	1.0×10^{-10} cm^3/s	Estimate
C30	$He(^3S_1) + H_2O \rightarrow H_2O^+ + He + e$	1.0×10^{-10} cm^3/s	Estimate

D. POSITIVE-ION ELECTRON RECOMBINATION: N^+, N_2^+, N_4^+

NUMBER	REACTION	REACTION RATE	REFERENCE
D1	$N^+ + e + e \rightarrow N + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10
D2	$N^+ + e + N_2 \rightarrow N + N_2$	$6.0 \times 10^{-27} \left(\frac{300}{T_e}\right)^{2.5}$ cm^6/s	DNA, 1979, p 24-10
D28	$N^+ + e + He \rightarrow N + He$	$2.0 \times 10^{-27} \left(\frac{300}{T_e}\right)^{2.5}$ cm^6/s	DNA, 1979, p 24-10
D3	$N_2^+ + e + e \rightarrow N_2 + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10
D4	$N_2^+ + e \rightarrow N + N$	$1.8 \times 10^{-7} \left(\frac{300}{T_e}\right)^{0.39}$ cm^3/s	DNA, 1979, p 24-11
D24	$N_4^+ + e + e \rightarrow N_2 + N_2 + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10
D5	$N_4^+ + e \rightarrow N_2 + N_2$	$2.0 \times 10^{-6} \left(\frac{300}{T_e}\right)^{1.0}$ cm^3/s	DNA, 1979, p 24-11

D. POSITIVE-ION ELECTRON RECOMBINATION: O^+, O_2^+, O_4^+

NUMBER	REACTION	REACTION RATE	REFERENCE
D6	$O^+ + e + e \rightarrow O + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10
D7	$O^+ + e + O_2 \rightarrow O + O_2$	$6.0 \times 10^{-27} \left(\frac{300}{T_e}\right)^{2.5}$ cm^6/s	DNA, 1979, p 24-10

D29	$O^+ + e + He \rightarrow O + He$	$6.0 \times 10^{-27} \left(\frac{300}{T_e}\right)^{2.5}$ cm^6/s	DNA, 1979, p 24-10
D8	$O_2^+ + e + e \rightarrow O_2 + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10
D9	$O_2^+ + e \rightarrow O + O$	$2.1 \times 10^{-7} \left(\frac{300}{T_e}\right)^{0.63}$ cm^3/s	DNA, 1979, p 24-10
D25	$O_4^+ + e + e \rightarrow O_2 + O_2 + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10
D10	$O_4^+ + e \rightarrow O + O + O_2$	$2.0 \times 10^{-6} \left(\frac{300}{T_e}\right)^{1.0}$ cm^3/s	DNA, 1979, p 24-11

D. POSITIVE-ION ELECTRON RECOMBINATION: $He^+, He_2^+, NO^+, H_3O^+$

NUMBER	REACTION	REACTION RATE	REFERENCE
D11	$He^+ + e + e \rightarrow He + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10
D27	$He^+ + e + e \rightarrow He(^3S_1) + e$	$3.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	Cheret and Lambert, 1971
D23	$He_2^+ + e + e \rightarrow He + He + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10
D12	$He_2^+ + e \rightarrow He + He$	1.0×10^{-8} cm^3/s	Delpech, 1973
D13	$He_2^+ + e + He \rightarrow 3He$	2.0×10^{-27} cm^6/s	Delpech, 1973
D14	$NO^+ + e + e \rightarrow NO + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10

D15	$NO^+ + e \rightarrow N + O$	$4.0 \times 10^{-7} \left(\frac{300}{T_e}\right)^{0.4}$ cm^3/s	DNA, 1979, p 24-11
D16	$H_3O^+ + e + e \rightarrow H_2O + H + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10
D17	$H_3O^+ + e \rightarrow H_2O + H$	$1.3 \times 10^{-6} \left(\frac{300}{T_e}\right)^{1.0}$ cm^3/s	DNA, 1979, p 24-12

D. POSITIVE-ION ELECTRON RECOMBINATION: $O_2^+ \bullet H_2O$, $H_3O^+ \bullet OH$, $H_3O^+ \bullet H_2O$

NUMBER	REACTION	REACTION RATE	REFERENCE
D26	$O_2^+ \bullet H_2O + e + e \rightarrow O_2 + H_2O + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10
D18	$O_2^+ \bullet H_2O + e \rightarrow O_2 + H_2O$	$1.5 \times 10^{-6} \left(\frac{300}{T_e}\right)^{0.2}$ cm^3/s	DNA, 1979, p 24-11
D19	$H_3O^+ \bullet OH + e + e \rightarrow H_2O + OH + H + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10
D20	$H_3O^+ \bullet OH + e \rightarrow H_2O + OH + H$	$2.0 \times 10^{-6} \left(\frac{300}{T_e}\right)^{0.2}$ cm^3/s	DNA, 1979, p 24-12
D21	$H_3O^+ \bullet H_2O + e + e \rightarrow 2H_2O + H + e$	$7.0 \times 10^{-20} \left(\frac{300}{T_e}\right)^{4.5}$ cm^6/s	DNA, 1979, p 24-10
D22	$H_3O^+ \bullet H_2O + e \rightarrow 2H_2O + H$	$2.8 \times 10^{-6} \left(\frac{300}{T_e}\right)^{0.15}$ cm^3/s	DNA, 1979, p 24-12

E. TWO-BODY POSITIVE-ION NEGATIVE-ION RECOMBINATION: N^+, N_2^+, O^+

NUMBER	REACTION	REACTION RATE	REFERENCE
E1	$N^+ + O^- \rightarrow N + O$	$2.6 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-12
E2	$N_2^+ + O_2^- \rightarrow N_2 + O_2$	$1.6 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13
E3	$O^+ + O^- \rightarrow O + O$	$2.7 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-12

E. TWO-BODY POSITIVE-ION NEGATIVE-ION RECOMBINATION: O_2^+, O_4^+

NUMBER	REACTION	REACTION RATE	REFERENCE
E4	$O_2^+ + O^- \rightarrow O_2 + O$	$1.0 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-12
E5	$O_2^+ + O_2^- \rightarrow O_2 + O_2$	$4.2 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13
E8	$O_2^+ + NO_2^- \rightarrow O_2 + NO_2$	$4.1 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13
E9	$O_2^+ + NO_3^- \rightarrow O_2 + NO_3$	$1.3 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13
E12	$O_2^+ + NO_3^- \bullet H_2O \rightarrow NO_3 + H_2O + O_2$	$1.0 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13
E13	$O_4^+ + NO_3^- \bullet H_2O \rightarrow NO_3 + H_2O + O_2 + O_2$	$1.0 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13

E. TWO-BODY POSITIVE-ION NEGATIVE-ION RECOMBINATION: $NO^+, O_2^+ \bullet H_2O$

NUMBER	REACTION	REACTION RATE	REFERENCE
E6	$NO^+ + O^- \rightarrow NO + O$	$4.9 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13
E7	$NO^+ + O_2^- \rightarrow NO + O_2$	$6.0 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13
E10	$NO^+ + NO_2^- \rightarrow NO + NO_2$	$1.0 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13
E11	$NO^+ + NO_3^- \rightarrow NO + NO_3$	$9.0 \times 10^{-8} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13
E15	$NO^+ + NO_3^- \bullet H_2O \rightarrow NO_3 + H_2O + NO$	$1.0 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13
E14	$O_2^+ \bullet H_2O + NO_3^- \bullet H_2O \rightarrow NO_3 + H_2O + H_2O + O_2$	$1.0 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13

E. TWO-BODY POSITIVE-ION NEGATIVE-ION RECOMBINATION: $H_3O^+ \bullet H_2O, H_3O^+ \bullet OH$

NUMBER	REACTION	REACTION RATE	REFERENCE
E17	$H_3O^+ \bullet H_2O + NO_3^- \bullet H_2O \rightarrow NO_3 + H_2O + H_2O + H_2O + H$	$1.0 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13
E16	$H_3O^+ \bullet OH + NO_3^- \bullet H_2O \rightarrow NO_3 + H_2O + H_2O + H_2O$	$1.0 \times 10^{-7} \left(\frac{300}{T_{air}}\right)^{0.5}$ cm^3/s	DNA, 1979, p 24-13

F. THREE-BODY CLUSTER-ION RECOMBINATION: O_2^+

REFERENCE: DNA, 1979, p 24-13

NUMBER	REACTION	REACTION RATE
F1	$O_2^+ + O_3^- + N_2 \rightarrow 2O_2 + O + N_2$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$
F2	$O_2^+ + O_4^- + N_2 \rightarrow 3O_2 + N_2$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$
F3	$O_2^+ + CO_3^- + N_2 \rightarrow O_2 + CO_2 + O + N_2$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$
F4	$O_2^+ + CO_4^- + N_2 \rightarrow 2O_2 + CO_2 + N_2$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$
F5	$O_2^+ + O_2^- \bullet H_2O + N_2 \rightarrow 2O_2 + H_2O + N_2$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$
F32	$O_2^+ + O_3^- + He \rightarrow 2O_2 + O + He$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$
F33	$O_2^+ + O_4^- + He \rightarrow 3O_2 + He$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$
F34	$O_2^+ + CO_3^- + He \rightarrow O_2 + CO_2 + O + He$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$
F35	$O_2^+ + CO_4^- + He \rightarrow 2O_2 + CO_2 + He$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$
F36	$O_2^+ + O_2^- \bullet H_2O + He \rightarrow 2O_2 + H_2O + He$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$

F. THREE-BODY CLUSTER-ION RECOMBINATION: O_4^+

REFERENCE: DNA, 1979, p 24-13

NUMBER	REACTION	REACTION RATE
F6	$O_4^+ + O^- + N_2 \rightarrow 2O_2 + O + N_2$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$
F7	$O_4^+ + O_2^- + N_2 \rightarrow 3O_2 + N_2$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$
F8	$O_4^+ + O_3^- + N_2 \rightarrow 2O_2 + O_3 + N_2$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$
F9	$O_4^+ + O_4^- + N_2 \rightarrow 4O_2 + N_2$	$1.0 \times 10^{-25}\,(300/T_{air})^{2.5}\ cm^6/s$

F37	$O_4^+ + O^- + He \rightarrow 2O_2 + O + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F38	$O_4^+ + O_2^- + He \rightarrow 3O_2 + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F39	$O_4^+ + O_3^- + He \rightarrow 2O_2 + O_3 + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F40	$O_4^+ + O_4^- + He \rightarrow 4O_2 + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$

F. THREE-BODY CLUSTER-ION RECOMBINATION: NO^+

REFERENCE: DNA, 1979, p 24-13

NUMBER	REACTION	REACTION RATE
F10	$NO^+ + O_3^- + N_2 \rightarrow NO + O_2 + O + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F11	$NO^+ + O_4^- + N_2 \rightarrow NO + 2O_2 + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F12	$NO^+ + CO_3^- + N_2 \rightarrow NO + CO_2 + O + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F13	$NO^+ + CO_4^- + N_2 \rightarrow NO + CO_2 + O_2 + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F14	$NO^+ + O_2^- \bullet H_2O + N_2 \rightarrow NO + H_2O + O + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F15	$NO^+ + CO_3^- \bullet H_2O + N_2 \rightarrow NO + H_2O + CO_2 + O + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F16	$NO^+ + CO_4^- \bullet H_2O + N_2 \rightarrow NO + H_2O + CO_2 + O_2 + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F41	$NO^+ + O_3^- + He \rightarrow NO + O_2 + O + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F42	$NO^+ + O_4^- + He \rightarrow NO + 2O_2 + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F43	$NO^+ + CO_3^- + He \rightarrow NO + CO_2 + O + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F44	$NO^+ + CO_4^- + He \rightarrow NO + CO_2 + O_2 + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F45	$NO^+ + O_2^- \bullet H_2O + He \rightarrow NO + H_2O + O + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F46	$NO^+ + CO_3^- \bullet H_2O + He \rightarrow NO + H_2O + CO_2 + O + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F47	$NO^+ + CO_4^- \bullet H_2O + He \rightarrow NO + H_2O + CO_2 + O_2 + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$

F. THREE-BODY CLUSTER-ION RECOMBINATION: $O_2^+ \bullet H_2O$

REFERENCE: DNA, 1979, p 24-13

NUMBER	REACTION	REACTION RATE
F17	$O_2^+ \bullet H_2O + O^- + N_2 \rightarrow O_2 + H_2O + O + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F18	$O_2^+ \bullet H_2O + O_2^- + N_2 \rightarrow 2O_2 + H_2O + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F19	$O_2^+ \bullet H_2O + O_3^- + N_2 \rightarrow O_2 + O_3 + H_2O + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F20	$O_2^+ \bullet H_2O + CO_3^- + N_2 \rightarrow O_2 + O + H_2O + CO_2 + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F21	$O_2^+ \bullet H_2O + CO_4^- + N_2 \rightarrow 2O_2 + H_2O + CO_2 + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F22	$O_2^+ \bullet H_2O + O_2^- \bullet H_2O + N_2 \rightarrow 2O_2 + 2H_2O + N_2$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F48	$O_2^+ \bullet H_2O + O^- + He \rightarrow O_2 + H_2O + O + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F49	$O_2^+ \bullet H_2O + O_2^- + He \rightarrow 2O_2 + H_2O + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F50	$O_2^+ \bullet H_2O + O_3^- + He \rightarrow O_2 + O_3 + H_2O + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F51	$O_2^+ \bullet H_2O + CO_3^- + He \rightarrow O_2 + O + H_2O + CO_2 + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F52	$O_2^+ \bullet H_2O + CO_4^- + He \rightarrow 2O_2 + H_2O + CO_2 + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$
F53	$O_2^+ \bullet H_2O + O_2^- \bullet H_2O + He \rightarrow 2O_2 + 2H_2O + He$	$1.0 \times 10^{-25}\ (300/T_{air})^{2.5}\ cm^6/s$

F. THREE-BODY CLUSTER-ION RECOMBINATION: $H_3O^+ \bullet H_2O$

REFERENCE: DNA, 1979, p 24-13

NUMBER	REACTION	REACTION RATE
F23	$H_3O^+ \bullet H_2O + O^- + N_2 \rightarrow 2H_2O + OH + N_2$	$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s
F24	$H_3O^+ \bullet H_2O + O_2^- + N_2 \rightarrow 2H_2O + OH + O + N_2$	$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s
F25	$H_3O^+ \bullet H_2O + O_3^- + N_2 \rightarrow 2H_2O + OH + O_2 + N_2$	$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s
F26	$H_3O^+ \bullet H_2O + O_4^- + N_2 \rightarrow 2H_2O + OH + O_3 + N_2$	$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s
F27	$H_3O^+ \bullet H_2O + CO_3^- + N_2 \rightarrow 2H_2O + OH + CO_2 + N_2$	$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s
F28	$H_3O^+ \bullet H_2O + CO_4^- + N_2 \rightarrow 2H_2O + OH + CO_2 + O + N_2$	$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s
F29	$H_3O^+ \bullet H_2O + O_2^- \bullet H_2O + N_2 \rightarrow 3H_2O + OH + O + N_2$	$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s
F30	$H_3O^+ \bullet H_2O + CO_3^- \bullet H_2O + N_2 \rightarrow 3H_2O + OH + CO_2 + N_2$	$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s
F31	$H_3O^+ \bullet H_2O + CO_4^- \bullet H_2O + N_2 \rightarrow 3H_2O + OH + CO_2 + O + N_2$	$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s
F54	$H_3O^+ \bullet H_2O + O^- + He \rightarrow 2H_2O + OH + He$	$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s
F55	$H_3O^+ \bullet H_2O + O_2^- + He \rightarrow 2H_2O + OH + O + He$	$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s
F56	$H_3O^+ \bullet H_2O + O_3^- + He \rightarrow 2H_2O + OH + O_2 + He$	$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s

F57 $H_3O^+ \bullet H_2O + O_4^- + He \rightarrow 2H_2O + OH + O_3 + He$

$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s

F58 $H_3O^+ \bullet H_2O + CO_3^- + He \rightarrow 2H_2O + OH + CO_2 + He$

$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s

F59 $H_3O^+ \bullet H_2O + CO_4^- + He \rightarrow 2H_2O + OH + CO_2 + O + He$

$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s

F60 $H_3O^+ \bullet H_2O + O_2^- \bullet H_2O + He \rightarrow 3H_2O + OH + O + He$

$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s

F61 $H_3O^+ \bullet H_2O + CO_3^- \bullet H_2O + He \rightarrow 3H_2O + OH + CO_2 + He$

$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s

F62 $H_3O^+ \bullet H_2O + CO_4^- \bullet H_2O + He \rightarrow 3H_2O + OH + CO_2 + O + He$

$1.0 \times 10^{-25} (300/T_{air})^{2.5}$ cm^6/s

G. ELECTRON IMPACT IONIZATION, METASTABLE PRODUCTION, AND VIBRATIONAL EXCITATION

NUMBER	REACTION	REACTION RATE	REFERENCE
G1	$e + O_2 \rightarrow e + e + O_2^+$	Graphs	Lowke, 1992
G2	$e + O_2 \rightarrow e + O_2(a^1\Delta_g)$	Graphs	Lowke, 1992
G25	$e + O_2 \rightarrow e + O_2(b^1\Sigma_g^+)$	Table	Masek *et al*, 1978
G26	$e + NO \rightarrow e + e + NO^+$	Cross Sections	Lindsay *et al*, 2000.
G3	$e + N_2(v = 0) \rightarrow e + N_2(v = 1)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G4	$e + N_2(v = 0) \rightarrow e + N_2(v = 2)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G5	$e + N_2(v = 0) \rightarrow e + N_2(v = 3)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G6	$e + N_2(v = 0) \rightarrow e + N_2(v = 4)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G7	$e + O_2(v = 0) \rightarrow e + O_2(v = 1)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (B)
G8	$e + O_2(v = 0) \rightarrow e + O_2(v = 2)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (B)
G9	$e + O_2(v = 0) \rightarrow e + O_2(v = 3)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (B)
G10	$e + O_2(v = 0) \rightarrow e + O_2(v = 4)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (B)
G11	$e + N_2(v = 1) \rightarrow e + N_2(v = 0)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G12	$e + N_2(v = 1) \rightarrow e + N_2(v = 2)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)

G13	$e + N_2(v=2) \to e + N_2(v=0)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G14	$e + N_2(v=2) \to e + N_2(v=1)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G15	$e + N_2(v=1) \to e + N_2(v=3)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G16	$e + N_2(v=3) \to e + N_2(v=0)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G17	$e + N_2(v=3) \to e + N_2(v=1)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G18	$e + N_2(v=1) \to e + N_2(v=4)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G19	$e + N_2(v=4) \to e + N_2(v=0)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G20	$e + N_2(v=4) \to e + N_2(v=1)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (A)
G21	$e + O_2(v=1) \to e + O_2(v=0)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (B)
G22	$e + O_2(v=2) \to e + O_2(v=0)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (B)
G23	$e + O_2(v=3) \to e + O_2(v=0)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (B)
G24	$e + O_2(v=4) \to e + O_2(v=0)$	Tables	Aleksandrov *et al*, 1981
		Graphs	Pavlov, 1998 (B)

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